THE OCEANOGRAPHY OF

SANTA MONICA BAY, CALIFORNIA

Volume I

by

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and

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A Final Report

submitted to the Hyperion Engineers,

by the Geology Department,

University of Southern California

September 18, 1956

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PREFACE

In June 1955, when marine scientists at the University of Southern California were called upon to conduct an oceanographic survey of Santa Monica Bay, sanitary engineers considered that by disposing sewage five miles from the shore the effluent would be adequately diluted by the great volume of sea water available, and that such dilutions would eliminate any health hazard on the adjacent shores. Within a few months, however, it was necessary to change this philosophy, for by this time it had been determined from numerous current measurements that the ocean in Santa Monica Bay moved too slowly to give dilutions of greater than 1:100 despite the method of mechanical diffusion used.

It was essential, therefore, that the scientists at the University initiate a program to investigate the rate of disappearance of coliform bacteria from sea water, and to determine the direction and net flow of the ocean currents in the bay. These parts of the eventual overall program were begun in September 1955 and completed in July 1956. New techniques were devised and used for the first time at sea, and the results were believed to be highly successful.

Nearly 1,500 stations were occuppied by the M/V VELERO IV, the University's research vessel, during the year. Some of the stations were occuppied for only a short period and for one purpose, while at other times,

20 to 24 hours were spent making observations at one locality. Work was conducted both during daylight hours and at night in an attempt to eliminate inherent errors in investigations limited to only one period of the day.

The results of this survey are embodied in six separate reports covering bacteriology, marine biology, submarine geology, oceanography, and the data in appendix form.

The several fields of interest covered by the survey required the capabilities of a number of experts who specialize in the marine sciences. The following personnel at the University of Southern California contributed either full or part time to the survey work:

Dr. K. O. Emery, Marine Geologist

Dr. Olga Hartman, Marine Biologist

Dr. Daniel Ivler, Bacteriologist

Dr. T. Mitwer, Bacteriologist

Dr. Sydney C. Rittenberg, Marine Bacteriologist

Dr. Robert E. Stevenson, Geological Oceanographer

Dr. Richard B. Tibby, Physical Oceanographer

Mr. D. Brostoff, Bacteriologist

Mr. John V. Byrne, Marine Geologist

Mr. Donn S. Gorsline, Marine Geologist

Mr. John R. Grady, Marine Geologist

Mr. L. Hoachstein, Bacteriologist

Mr. P. Kramer, Bacteriologist

Mr. R. MacGlasson, Laboratory Technician

Mr. B. Mechalas, Bacteriologist

Mr. R. J. Martinez, Bacteriologist

Miss Sandy Lynagh, Technical Secretary

Miss Johanna Resig, Microbiologist

Mr. D. Scholl, Laboratory Technician

Mr. Richard D. Terry, Marine Geologist

Mr. Elazar Uchupi, Marine Geologist

Mr. E. Zalesny, Laboratory Technician

Respectfully submitted,

Robert E. Stevenson

Robert E. Stevenson
Director, Inshore Research

September 18, 1956

THE OCEANOGRAPHY OF SANTA MONICA BAY

INTRODUCTION

In the summer of 1955 the University of Southern California was requested by Hyperion Engineers, Inc. to furnish information on Santa Monica Bay which would assist in the design of a proposed oceanic sewage outfall for the City of Los Angeles. The existing Hyperion treatment plant, placed in operation in 1950, has an average design capacity of 245 million gallons of sewage per day, which is treated by primary settling followed by the high rate activated sludge process. The treatment is supplemented by chlorination when necessary. The outfall from this plant terminates one mile from shore. Because of the unprecedented growth in the Los Angeles area this rate of flow soon was reached and it was therefore necessary to provide for the eventual disposal by the year 2000 of an average of 640 million gallons per day. A number of alternative schemes were proposed for taking care of this enormous quantity of sewage. However, the one which was considered to be most economical recommended increasing the capacity of the present Hyperion plant and disposing the sludge and primary-treated effluent through separate ocean outfalls terminating at distances of five to six miles from the shore of Santa Monica Bay.

The University was engaged by Hyperion Engineers, Inc. to supply data on bottom topography, sediments, and hydrographic features of Santa Monica Bay which were directly related to the design and construction of the outfalls. However, within a short time it became apparent that additional information on

ocean currents, temperatures, and certain other characteristics of the bay would be required. Shortly thereafter a study of the types and distribution of bottom-dwelling animals was included and finally, in October of 1955, the contract was further extended to include an investigation of the rate of disappearance of coliform bacteria in the sea from unchlorinated primary-treated effluent.

It has been the contractual responsibility of the University of Southern California, after a period of one year's research in the bay, to report to Hyperion Engineers, Inc. the scientific results on the following specific topics:

1. The detailed bottom topography and sedimentary characteristics of the sea floor.
2. The biology of bottom-dwelling animals.
3. The distribution and rate of disappearance of coliform bacteria.
4. The temperature, salinity, turbidity, and other properties of the water within the bay.
5. The directions and velocities of ocean currents.

The submarine topography and sediments, the biology of bottom organisms, and the bacterial studies are contained in separate sections of this report.

In addition to those items, a review of the climate, sea and swell, and other meteorological conditions have been included. Because both the data and the descriptive material for this review were readily available, such a review could be made without interfering with major research commitments.

Santa Monica Bay, California, is a crescent-shaped indentation of the southern California coast, lying due west of the

City of Los Angeles. The seaward boundary of the bay extends from Point Dume on the north to Palos Verdes Point on the south, a distance of 27 statute miles. The coast line of the bay is approximately 38 miles in length. The eastern shore is heavily populated and the cities of Santa Monica, Venice, Playa del Rey, El Segundo, Manhattan Beach, Hermosa Beach, and Redondo extend almost continuously for a distance of 15 miles from north to south. Along the northern border of the bay the Santa Monica Mountains reach the shore and the main access to this area is by a north-south highway. Only relatively small and scattered communities have been built along the northern shores, mostly in the vicinity of Malibu, although the area is much used for recreational purposes. The southern shore consists of 3 miles of precipitous cliffs above a narrow, rocky beach, cut into the Palos Verdes Hills.

Like the alluvial Los Angeles plain to the east, the bottom of the bay slopes gently from the shore to a depth of 300 feet, forming a shelf 3 to 6 miles wide. In the central portion of the bay, between Playa del Rey and Hermosa Beach, the shelf extends farther to sea and forms a submarine plain, projecting to a distance of 10 miles from shore.

The shelf is incised by two major submarine canyons, one to the north and one to the south of the central shelf extension. The Santa Monica Canyon is wide and the walls are not steep except at the head of the canyon at a distance of 4½ miles from shore. The Redondo Canyon is a well-defined physiographic feature of the submarine landscape. It has relatively steep sides and its major head extends almost to shore at Redondo Beach.

A number of offshore islands protect the area of Santa Monica Bay from the effects of storms and high waves originating in the open sea. From a hydrographic standpoint, the bay is in open communication with the offshore region and the character of its waters as well as its circulation, therefore, depend upon events outside the bay. On the other hand, its shape and orientation are such that waves, tides, and local winds decisively modify the pattern of current flow, particularly in the near-shore and littoral zones. Although the chemical and physical structure of the waters in the bay are complicated, the work of the past year has established certain general features and patterns of flow that are the subject of this report.

THE CLIMATE OF SANTA MONICA BAY

Los Angeles is situated in a region which has a "Mediterranean" climate (Köppen, 1923). The characteristics of this climate are hot summers, with the warmest month having an average temperature higher than 71°F, mild winters with the coolest month having average temperatures between 32°F and 64.4°F, and with at least three times as much rainfall in the wettest month as in the dryest. The coastal regions of southern California have all the prerequisites for such a climate. Due to the concentration of rainfall in the winter and early spring, plus the hot dry summers, the vegetation imparts a brown color to the land area during most of the year. Only in the late winter and early spring is the landscape green, and the duration of the green period is entirely

dependent on the amount and spacing of rainfall for the particular year.

Chief among the meteorological factors influencing the southern California climate is the prevalence in the vicinity throughout most of the year of the eastern lobe of the Pacific High. When it is strong and lies close to the shore, clear skies and mild weather previal since it causes storms from the North Pacific to be turned eastward before reaching this latitude. As the strength of the high weakens, or if it moves to the south or west, cold fronts may sweep in from the northwest. During the summer when the high pressure belt has moved northward, these rarely arrive. If they do, they are quite weak. During the winter, however, the center of the high is usually about a third of the distance between Hawaii and the Aleutians. A col in the high pressure belt is located over the eastern margin of the Pacific which results in a strong northwesterly flow, and the southern parts of cyclones are able to reach our coasts bringing fairly strong winds and rain.

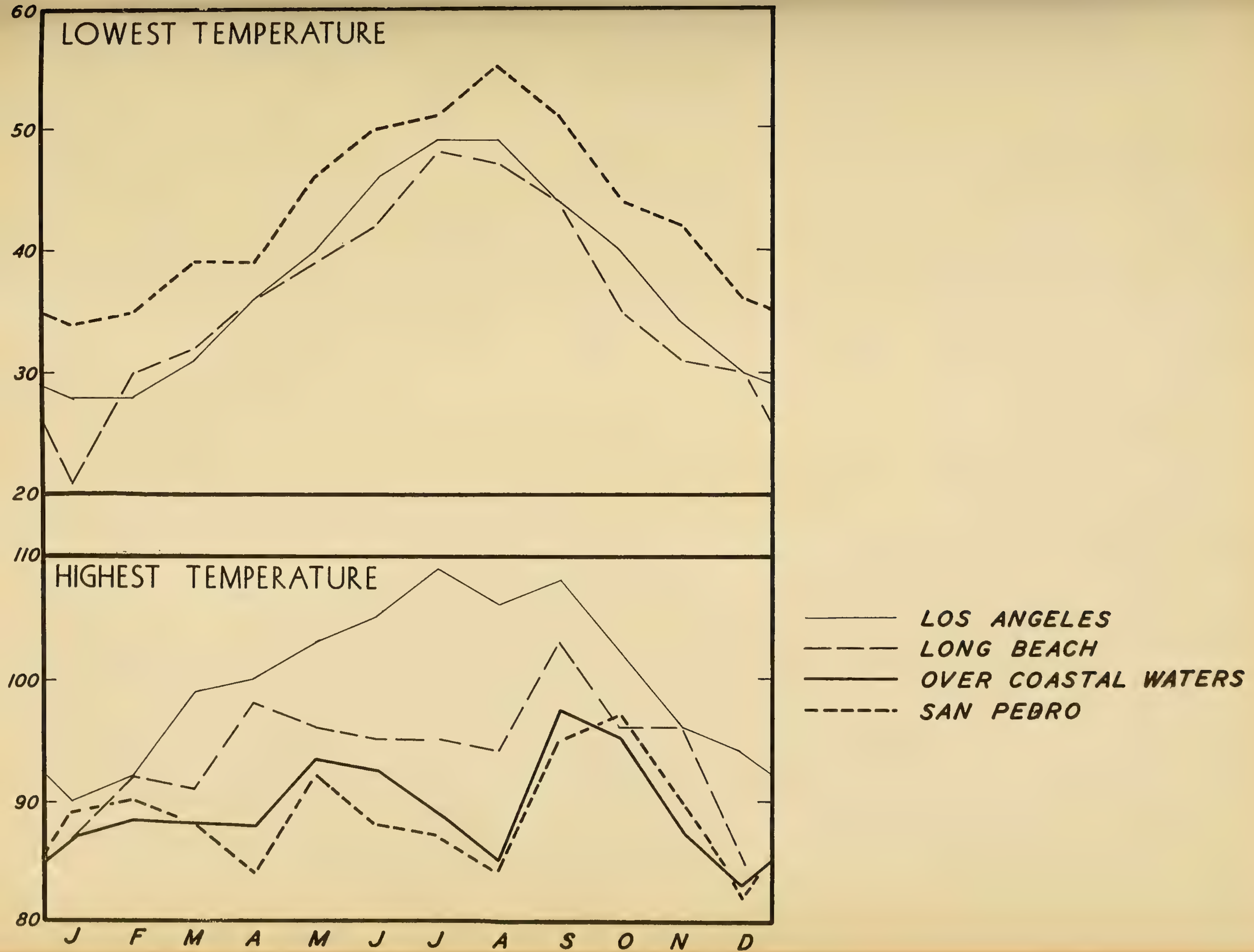
This northwesterly flow is apt to be as strong in summer as in winter, but in the summer the trajectory of an air particle would take it back to a position nearer the center of the high pressure cell. Even though northwesterly winds prevail, therefore, they do not originate in the North Pacific and accordingly do not bring the cold fronts to the coast. In the summer, the intensity of the northwesterlies may be increased by the development of a deep thermal low over the arid regions of the southwestern United States. It is not

uncommon in late August and September for the pressure gradient to become so steep over the water adjacent to Point Conception that winds of Force 4, 5, and even 6 prevail for days on end due to this influence.

Precipitation is usually light and steady when it occurs and does not last more than two or three consecutive days, except under unusual meterologic conditions. Cumulus clouds, although rare over the Los Angeles area, frequently build to considerable heights over the coastal mountains during the fall and spring months. Thunderstorms occur less than three times a year in Los Angeles and have never been recorded over Santa Monica Bay. Most precipitation comes from cold frontal activity, as warm fronts are normally not extensive enough to reach this latitude with any intensity.

In Santa Monica Bay, climatic characteristics are even milder than that of the bordering coastal areas. The highest, lowest, and average temperatures are shown in Figure 1 for coastal stations, and for the San Pedro Channel in Figure 2. The annual range at the coast is a moderate 23.3°F, and the mean minimum and maximum temperatures have a spread of only 18°F. The lowest temperature ever recorded along the Los Angeles coastal region was 28.2°F at San Pedro on January 23, 1937. Temperatures higher than 87°F have been recorded for every month of the year, and temperatures of 90°F or higher have occurred at one time or another in 9 of the 12 months. On the water temperatures are even milder. In nearly 30 years of operation, the Catalina Island Steamship Line has

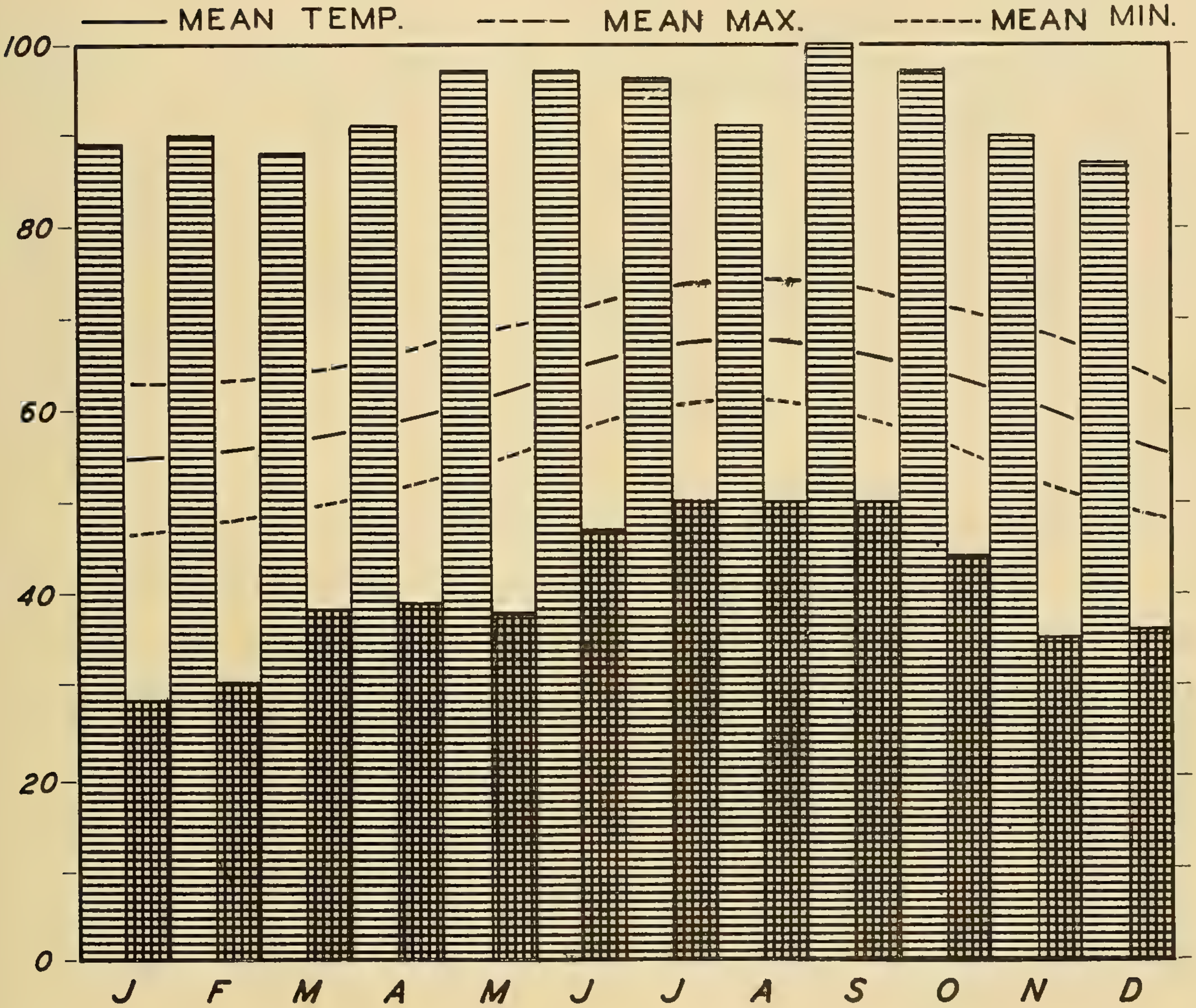
Figure 1. Maximum and minimum air temperatures.



LOWEST TEMPERATURE
HIGHEST TEMPERATURE
60
50
40
30
20
110
100
90
80
J F M A M J J A S O N D
LOS ANGELES
LONG BEACH
OVER COASTAL WATERS
SAN PEDRO

Figure 2. Maximum, minimum, and average air temperatures, San Pedro Channel.

HIGHEST AND LOWEST TEMPERATURE RECORDED



never reported a freezing temperature nor one higher than 87°F aboard their ships.

Precipitation is less along the coast than in Los Angeles and lower still over the waters of the continental shelf. There are no continuous records of rainfall over the ocean, but the figures for San Pedro probably give a close approximation (Fig. 3). At one time or another rain has fallen in every month of the year, but the summer months are quite dry. The average for June is 0.10 inch, for July, 0.01 inch, and for August, 0.05 inch. Even in February, the rainiest month, the average is less than 2.5 inches and the greatest precipitation over a 24 hour period produced a mere 3.5 inches.

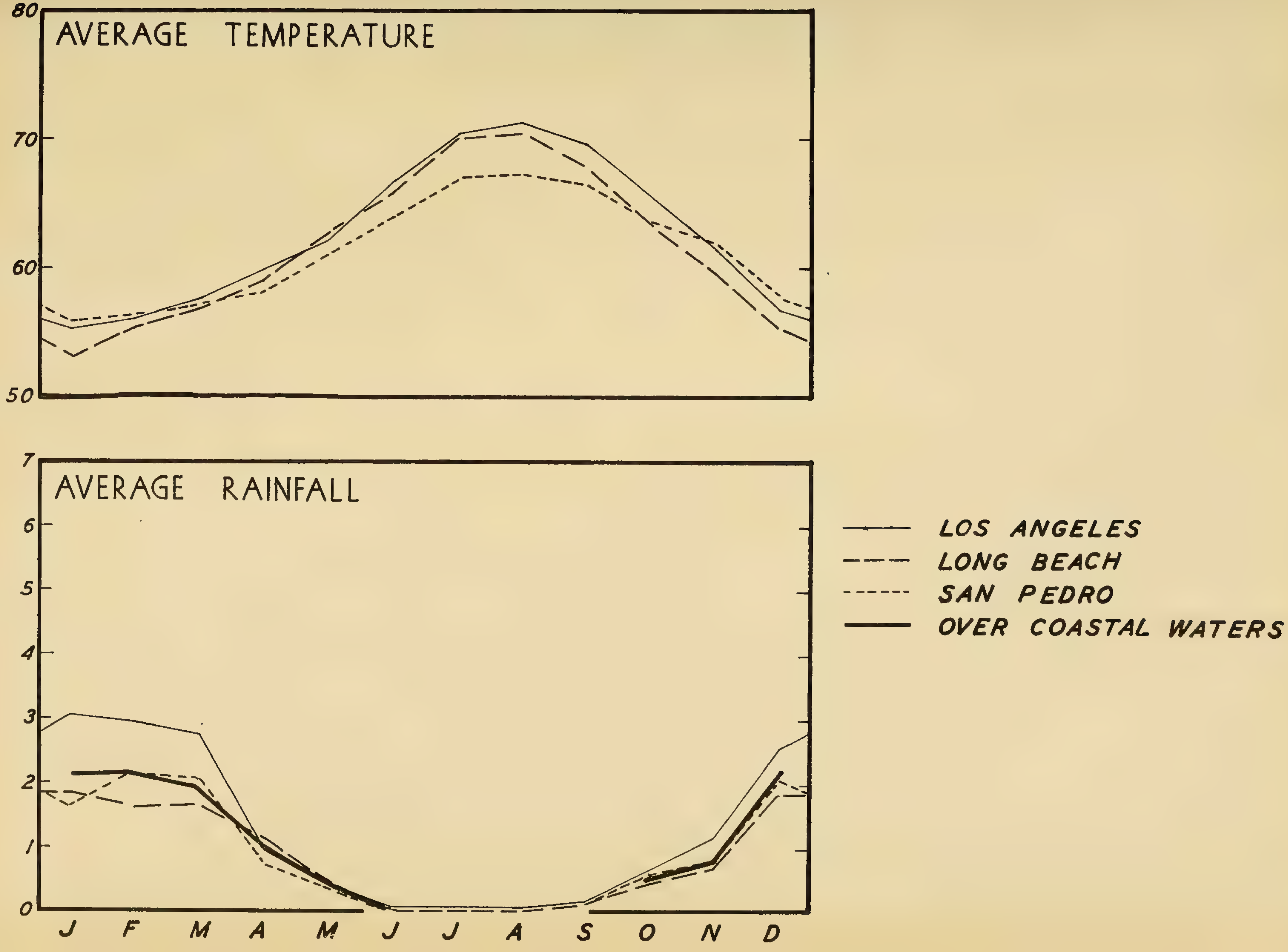
Sky Conditions

Data of the sky conditions on land are available from the U. S. Weather Bureau station at the Los Angeles International Airport and are shown in Figure 4. Even so, these do not represent the conditions prevalent over the coastal waters of Los Angeles. The sky and visibility conditions in Figure 4 were compiled from the logs of the Catalina Island steamers and represent an observation period of ten years.

January

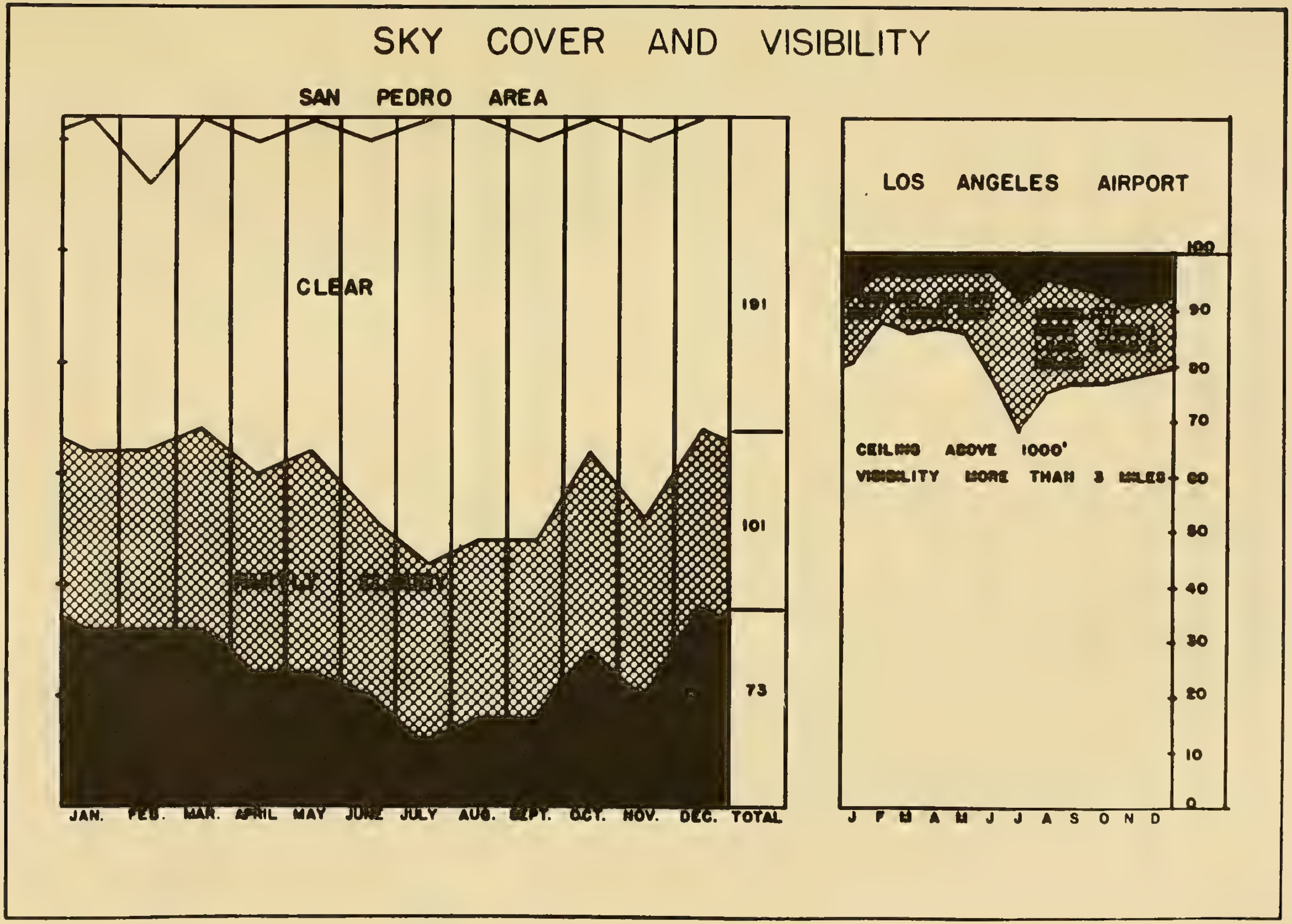
Fog is prevalent in January with 27% of the mornings (9 days) having ceilings below 500 feet and visibilities less than ½ mile. The fog usually changes to a low overcast or broken clouds by 1100 hours. Slightly more than two days a month have fog throughout a 24 hour period. However, in January 1950, a continuous fog was recorded lasting 94 hours,

Figure 3. Average air temperature and rainfall.



AVERAGE TEMPERATURE
80
70
60
50
AVERAGE RAINFALL
7
6
5
4
3
2
1
0
J F M A M J J A S O N D
LOS ANGELES
LONG BEACH
SAN PEDRO
OVER COASTAL WATERS

Figure 4. Sky conditions in the Los Angeles area.


SKY COVER AND VISIBILITY
SAN PEDRO AREA
CLEAR
191
101
73
JAN. FEB. MAR. APRIL MAY JUNE JULY AUG. SEPT. OCT. NOV. DEC. TOTAL
LOS ANGELES AIRPORT
CEILING ABOVE 1000'
VISIBILITY MORE THAN 3 MILES
100
90
80
70
60
50
40
30
20
10
0
J F M A M J J A S O N D

and it is not unknown in this month for fogs to last 3 to 6 days with only a 1 to 2 hour break near midday.

A low overcast with ceilings less than 1,000 feet but over 500 feet, and visibilities less than three miles is equally common. An average of 23% of the mornings and 18% of the afternoons have such an overcast. The stratus is continuous throughout a 24 hour period 12% of the time. These overcasts are seldom the result of fog lifting, but may precede a heavy fog. Although all-day overcasts do occur, as noted, the more common condition is for the stratus to "break" near midday, resulting in broken or clear skies. Scattered clouds are rare during any part of the year over waters of the continental shelf.

<u>February through July</u>

February marks the beginning of a trend in the decrease in the occurrence of fog. The decrease continues through July, and in the months of March, June, and July the occurrence of fog is negligible. April and May have a slight increase, particularly in the morning hours, but the increase is minor amounting to only two days. Fog during this part of the year is primarily a morning condition and normally dissipates late in the forenoon. In late April and early May, no fog has been recorded in the afternoon and in the entire months of March, June, and July no fog lasts throughout a 24 hour period. The maximum fog conditions in this part of the year occur in February and May when 12 and 9 per cent of the days, respectively, have fog during the morning hours.

Other overcast conditions also tend to decrease in February and March from those noted in January. In February, 21% of the mornings and 21% of the afternoons (6 days) are overcast and the stratus layer is continuous through 24 hours 12% of the month (4 days). Broken clouds show a marked decrease in occurrence in both months with none lasting 24 hours in February and only one recording in March.

Because of the decrease in overcasts there is a great increase in the number of clear days in the first two months of the period. In February, the sky is clear all day 62% of the time (21 days), and in March, 66% of the month is clear for 24 hours.

In April, the "summer sea fogs" begin to intrude the southern California coast, although these low stratus layers are more frequent in May, June, and August. The "sea fogs" are actually low-lying stratus layers of varying thickness and are called "high fogs" by the general public in the Los Angeles Basin area. Usually the stratus dissipates or "burns off" before noon, but there may be perioas during which a continuous overcast persists for a week or ten days. Although it is uncommon, the morning occurrence of stratus may be remarkably regular. There have been summer months during which an overcast occurred through most of the forenoon for 21 of the 30 days. In 1948, from the first of June to the first of September, only 18 of 93 mornings were clear. In July 1948, 19 consecutive mornings were foggy or cloudy, and from the 11th of August through the 4th of September, every morning was overcast, a total of 25 consecutive days. The ceilings of

these stratus layers vary from 600 to 800 feet at dawn, rise to 1,200 or 1,300 feet after sunrise, and are near 1,500 feet at the time of dissipation.

Despite the increase in the number of cloudy mornings, the summer months have a high percentage of clear days. If the afternoon periods are considered along with the 24 hour periods, it is noted that June has the least cloudiness and August the most. An average of 27 afternoons are clear in June and 14 all-day periods.

August through December

Fog conditions begin to increase in August and this trend more or less continues through the end of January. The trend is most obvious in 24-hour fogs. In August and September an average of 7 mornings each month have low visibility due to fog, a characteristic of these months. Whereas fog in the early summer months is extremely irregular in occurrence, in August and September regular sequences may occur. Records show many periods when fog occurs each morning for 5 to 8 days. However, there is only one recording of fog persisting throughout the day.

Afternoon fogs in these five months are irregular in occurrence and are generally the result of a noontime "lifting" of the fog to be followed by a "lowering" in the late afternoon. Under such conditions, a fog bank persists throughout the day 20 to 30 miles offshore and the "lifting" and "lowering" is the result of morning land breezes and afternoon sea breezes. During the midday break, the sky is hazy and visibility remains less than 3 miles.

The occurrence of overcasts decreases regularly during the period until in November and December, only 4 mornings a month are overcast. The extent of summer sea fogs also diminishes rapidly after October and during the later months of the year, most cloudy conditions are the result of infrequent frontal storms. The number of days with a broken sky increases slightly, the clouds being the remnants of the morning fogs.

The most striking climatic characteristic is the great increase of days with clear skies in October, November, and December. These conditions reach a maximum in November when 55% (21 days) of the month is clear all day long. This, with the 67% of the clear afternoons in December, indicates the fine weather to be expected in these two months.

Haze

An important and common deterrent to visibility over the coastal waters is the haze which precedes and proceeds fog and low stratus clouds. During the summer months in particular, haze is prevalent and thick over the adjacent land mass. Its occurrence cannot be missed due to the brownish tinge contributed by the addition of smoke and fumes to the atmosphere. Normally this "smog" does not occur over the ocean, but following several days of smog, a land breeze may carry it seaward.

The haze results from the stable air conditions, the strong temperature inversion, and the geography of the Los Angeles region. Turbulent unstable air masses tend to disrupt the inversion and allow the haze to dissipate. However, the normally stable marine air is held in check by the semi-circular

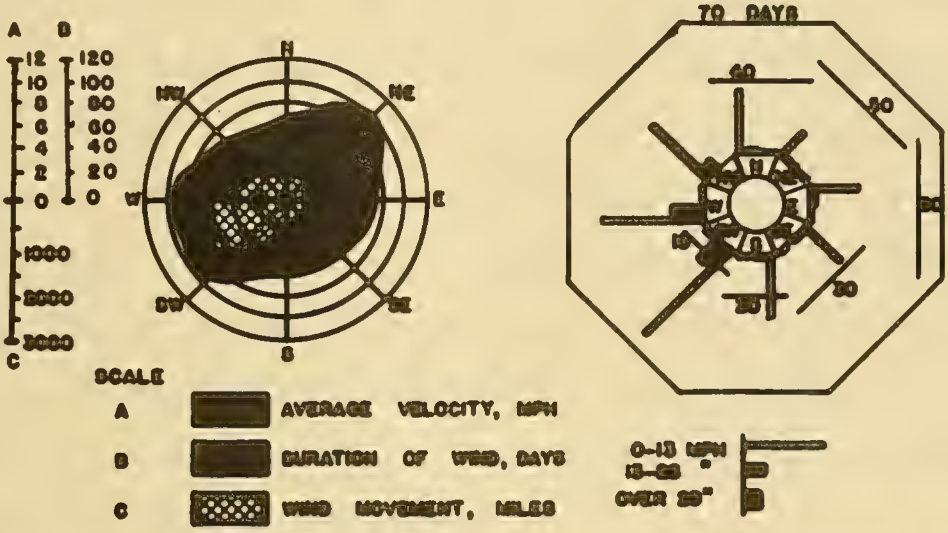
ring of mountains and with the inversion acting as a "lid", the haze may last for several weeks. Visibility in Santa Monica Bay during these periods is normally greater than 3 miles and less than 12 miles.

Wind Direction and Velocity

The dominant winds occur in the afternoon, are westerly, and are primarily the result of the land and sea breeze regime active along the coast. Higher velocities normally occur in the afternoons with the west winds, the land breezes at night from the east or northeast are usually less than Beaufort Force 2. Even Santanna wind conditions do not bring strong northeasterlies to this area as the force is much reduced after the air mass spreads out across the Los Angeles Plain. The wind conditions at Venice are similar to those noted at the Los Angeles International Airport and are known to be somewhat different from those obtained aboard the VELERO IV in Santa Monica Bay.

Wind conditions which are probably more representative of nearshore ocean areas are shown in Figure 5. This is a compilation from the monthly aerological records of the U. S. Navy aircraft carriers LEXINGTON and SARATOGA from April 1928 to July 1937. During this period the two ships were at an anchorage two miles seaward from Long Beach for a total time of 3.93 years. The winds were predominantly light with velocities less than 13 mph, and blew the greatest number of days from the southwest. For 60% of the year (219 days) the wind blew for more than 30 days, each from 5 different

Figure 5. Average yearly winds at Los Angeles Harbor.



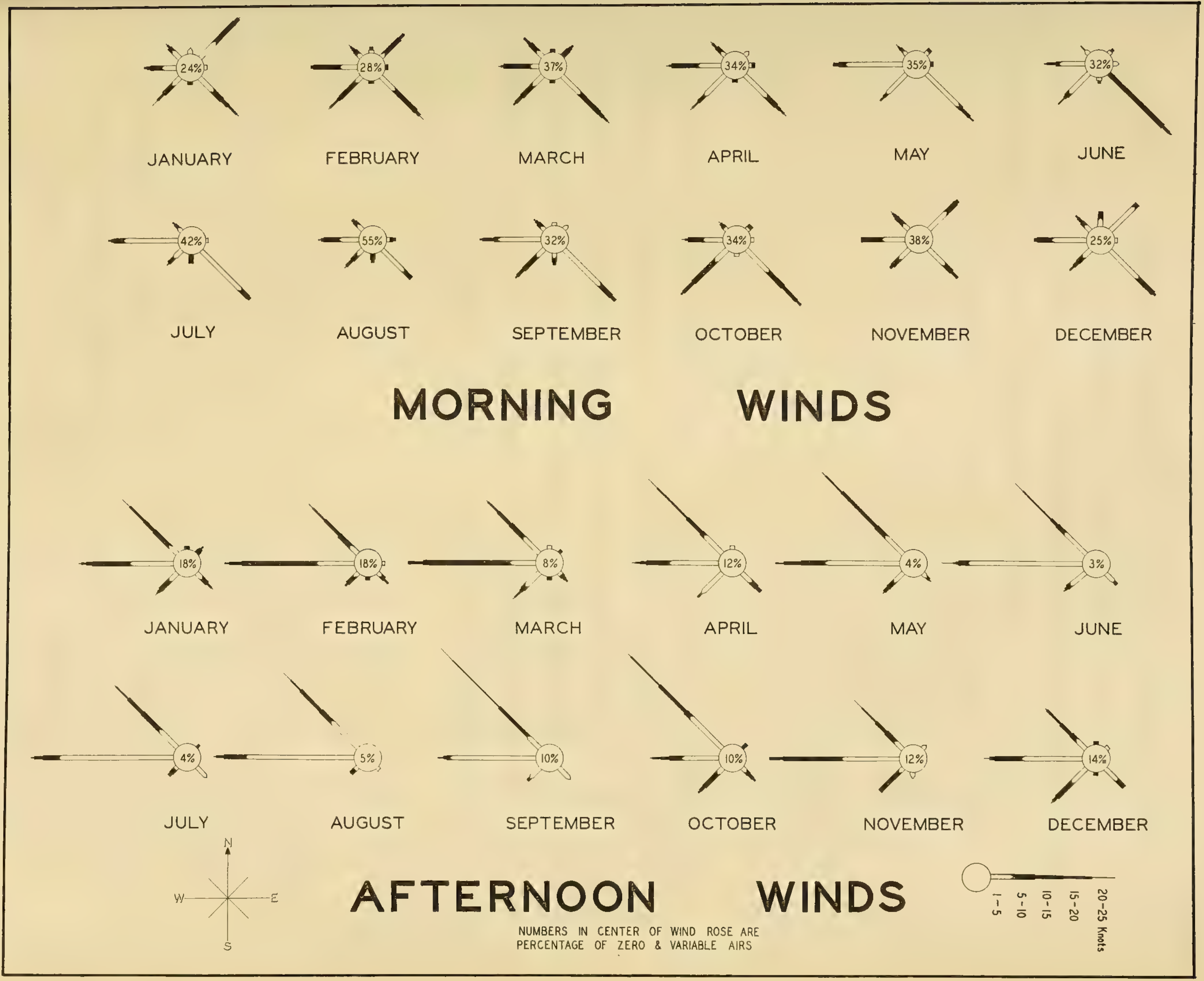
COMPILED FROM MONTHLY AEROLOGICAL RECORDS OF U.S.S. SARATOGA AND U.S.S LEXINGTON FROM APRIL, 1928 TO JULY, 1937. 3.33 YEARS OF OBSERVATIONS WERE RECORDED 2 MILES OFFSHORE. ONLY THESE RECORDS USED.

directions. However, for 33% of the year (120 days) the wind was from either the west or southwest, and from the duration of wind in days and the wind movement in miles, a prevailing wind from the southwest is indicated. These data do not show, though, the land breeze which is the dominant air motion in the morning hours throughout most of the year.

From information taken aboard the Catalina Island steamers, the S. S. CATALINA and the S. S. AVALON, wind directions and velocities have been compiled for morning and afternoon for each month. Even though the reporting station is approximately 8 miles south of San Pedro, a check with the winds obtained during 1955-56 aboard the VELERO IV in Santa Monica Bay show there to be no detectable variations other than those to be expected from year to year. These winds from the San Pedro Channel are shown in Figure 6.

During the later fall and winter months the morning is dominated by winds from the northeast and southeast while in the afternoon, west and northwest breezes prevail. In the spring, summer, and early fall, the morning northeast breeze is almost nonexistent and although the southeast wind continues to occur, its velocity is much lower. This change in the morning land breeze is due to the differential heating of the land during the summer and winter seasons. Because of the high temperatures over southern California in summer, a sea breeze blows at nearly all hours and the night cooling effect is shown mainly be a decrease in velocity of the sea breeze. It may also cause the sea breeze to cease blowing in the morning, this being indicated by the increase in calm mornings in the summer.

Figure 6. Monthly wind directions and velocities over the San Pedro Channel.


24%
JANUARY
28%
FEBRUARY
37%
MARCH
34%
APRIL
35%
MAY
32%
JUNE
42%
JULY
55%
AUGUST
32%
SEPTEMBER
34%
OCTOBER
38%
NOVEMBER
25%
DECEMBER
MORNING WINDS
18%
JANUARY
18%
FEBRUARY
8%
MARCH
12%
APRIL
4%
MAY
3%
JUNE
4%
JULY
5%
AUGUST
10%
SEPTEMBER
10%
OCTOBER
12%
NOVEMBER
14%
DECEMBER
N
W
E
S
AFTERNOON WINDS
NUMBERS IN CENTER OF WIND ROSE ARE PERCENTAGE OF ZERO & VARIABLE AIRS
1-5
5-10
10-15
15-20
20-25 Knots

Not so dramatic a change occurs in the afternoon winds between the summer and winter. The principle change is a shift to the northwest of the dominant winds during the summer accompanied by a slight increase in velocity. This is the result of the northward displacement of the permanent east Pacific high pressure area in the summer season and shifts the prevailing winds more or less parallel to the coast.

Winds from the north and south are rare and insignificant during all months. They are most noticeable in the winter when they result from frontal activity.

Winds of velocities greater than 30 knots are uncommon. When they do occur, they are winter frontal winds or northwest afternoon breezes of late summer and early fall. In more than ten years of observations by the Catalina Island steamers, only 4 days had winds with velocities greater than Force 5 on the Beaufort scale. In each case they were northwest winds.

SEA AND SWELL

Sea and swell are generated by winds and the differences between the two are determined by the proximity of the areas of generation to the region under consideration. An adequate understanding of the origin of local sea and swell can only be gained through knowledge of the meteorology involved.

The northwesterly air flow and the southwestern thermal low are the most important meteorological factors effecting the formation of local wind waves. They control to a large extent the movement of fronts and storm systems and are mainly

responsible for the intensity and orientation of the "trade winds" in the area just off the California coast.

The arrival of swell from distant storms is entirely independent of the local weather, so in the discussion of wave generation areas, only storms in the north and south Pacific Oceans which are of sufficient strength and properly situated to send waves to Santa Monica Bay are considered (Fig. 7).

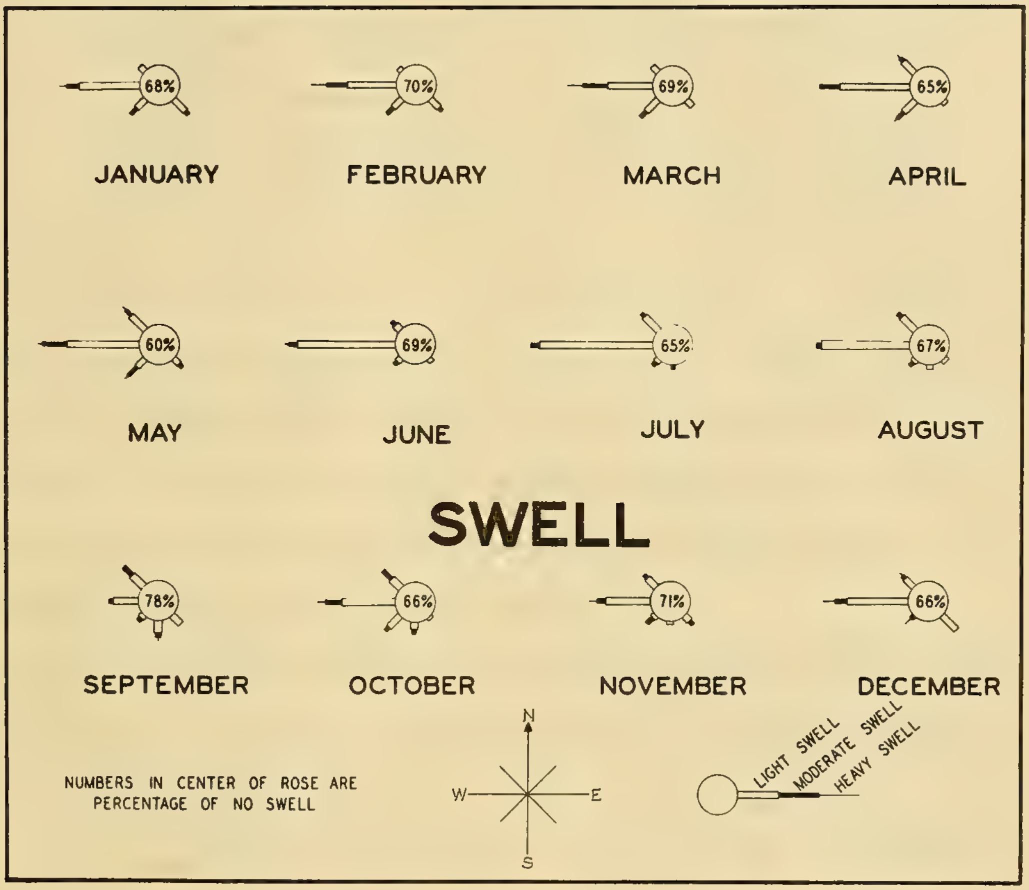
Wave Generation Areas

Southern Gulf of Alaska Cyclones

Most cyclones in the North Pacific Ocean originate in the vicinity of Japan and then move northeastwardly along the Aleutian Island chain, where many die out in the Aleution low pressure area. Most, however, succeed in reaching the Gulf of Alaska and some reach the North American continent. The area of strong winds in these cyclones is usually located in their southwest sectors so that heavy swell is sent out in a southeast direction toward the United States. This swell is unable to penetrate into Santa Monica Bay due to the configuration of the California coast. Probably about two-thirds of this moderate to heavy swell approaches from between 290° and 330°. Thus, Santa Monica Bay is ideally situated behind Point Arguello and Point Dume to be protected from swell of this origin.

If one of these storms takes an unusually southern route, swell from it will reach Point Dume. Even when this occurs, the swell will be greatly reduced in height by refraction around the point before entering the bay.

Figure 7. Frequency, height, and direction of swell, San Pedro Channel.


68%
JANUARY
70%
FEBRUARY
69%
MARCH
65%
APRIL
60%
MAY
69%
JUNE
65%
JULY
67%
AUGUST
SWELL
78%
SEPTEMBER
66%
OCTOBER
71%
NOVEMBER
66%
DECEMBER
NUMBERS IN CENTER OF ROSE ARE PERCENTAGE OF NO SWELL
N
W
E
S
LIGHT SWELL
MODERATE SWELL
HEAVY SWELL

A storm may also originate when the Polar Front trails southwestward and approaches the high pressure belt. If this occurs, warm maritime tropical air may be brought in contact with cold polar maritime air resulting in cyclogenesis, usually located about one third the distance between the Hawaiian and Aleutian Islands. If the contrast of the air masses is severe enough, cyclones may be formed which move eastwardly and eastnortheastwardly toward North America.

These secondary cyclones usually have strong westerly winds behind their cold fronts and heavy to moderate swell is sent on its way toward the southern California coast and may succeed in reaching the area by way of the Santa Barbara Channel. Swell with a 280° source and a 13 second period is representative from such an origin, and the direction and period is believed to be applicable also to those North Pacific storms which assume a southern track.

Storm tracks are farther south in the winter than in the summer, so there is a greater frequency of significant swell from these storms in the winter. Even in June and July, however, conditions may be such that this type of generation area is important.

The secondary cyclones mentioned above frequently occur in families so that as many as six similar storms may march across the ocean, all following a similar path. On such occasions, swell continues to arrive uninterrupted, but with fluctuations depending on the vagaries of each storm. At other times the secondary lows are diffuse and contain complicated frontal systems. With these conditions the winds are

apt to range considerably in direction and be fairly weak. Only light and moderate swell will accordingly be generated and dispatched toward Santa Monica Bay.

Two to three storms a month of this type occur on the average during the winter which dispatch significant swell to Santa Monica, and one to two in the summer.

North Boundary of the Pacific High

Whenever the Pacific High becomes elongated and migrates to the south, westerly winds blowing along its north flank generate waves which can reach the bay from bearings between about 225° and 280°. This situation is most likely to occur in the winter. Usually the winds are not greater than Force 4 in strength, and although the fetches and durations may be great, the resulting swell is moderate. Swell arriving from these areas may be expected to have periods of about 10 to 12 seconds and heights not exceeding three or four feet.

Since this generation area, and others associated with it, contribute swell from nearly westerly directions which is low and of only moderate length, it is of no great importance to the bay shore. In addition, its low frequency of occurrence should further bear this out, for it is estimated that it occurs only about once a month during the winter and somewhat less often in the summer.

Hawaiian Lows

The Hawaiian Lows originate in the expanse of ocean two or three hundred miles north of the Hawaiian Islands. Such lows are apt to remain stagnant for several days or even a week before moving slowly to the northeast. Winds within

these depressions may, at times, dispatch swell to the California coast, where it arrives with periods of 12 to 15 seconds from the westsouthwest, and with moderate heights (usually less than 8 feet). This type of storm occurs most frequently and with the greatest strength in the spring, although examples have been known throughout the year. The approximate frequency must give an annual average of about one storm a month, but with an irregular season distribution and from year to year.

Swell from these Hawaiian Lows arrives in Santa Monica Bay from between 225° and 280° with a period between 11 and 15 seconds.

Generation Areas in the Southern Hemisphere

Wave observations at the Scripps Institution of Oceanography indicate that swell often arrives from a bearing between south and southsoutheast and has an exceptionally low period of from 13 to 20 seconds. It is believed that this swell comes from generation areas in extratropical cyclones moving from west to east across the South Pacific Ocean between Australia and Chile. The lack of synoptic weather observations in that part of the world eliminates verification of this possibility (Nicholson, Grant, Shepard, and Crowell, 1946). However, the direction of wave travel leads either to an assumption of this source, or to consider it as having been generated by tropical storms. This last possibility is eliminated for the longer swell since the observed period at the California coast indicates a travel distance from 3,000 to 4,000 miles. The duration, fetches,

and wind velocities in tropical storms are not great enough to develop such long periods.

The summer maximum in the frequency of occurrence of this swell is quite reasonable, for the northern hemisphere summer corresponds to the southern winter when the storms there should be more intense and follow tracks farther to the north. It would accordingly be expected that if this were the source for these waves, the swell would be of greater significance in the northern summer.

This swell probably arrives about two-thirds of the time, but because it is usually low it is inconspicuous owing to the existence at the same time of local wind waves or more prominent swell from other generation areas. The presence of this type of swell in the summer is particularly evident, since during that season the contributions from other types is at a minimum. The sea breeze, on the other hand, has a greater frequency of occurrence and tends to have greater velocities in summer than in winter. Thus, the wind waves caused by it would tend to obscure the southern swell more often.

The Palos Verdes Hills lie in the path of the direction of approach of southern hemisphere swell and only occasionally is the swell of importance, even along the Malibu shore. Its arrival along the Redondo-Santa Monica shoreline is negligible and likely non-existent.

Tropical Hurricanes

In the summer and fall, tropical storms are apt to originate in the oceanic area off the coast of Costa Rica. Nine-tenths of these storms travel northwest from their place of

origin, but have dissipated long before reaching southern California. Nevertheless, some send swell toward the coast with a period of 9 to 11 seconds. This swell differs from the southern hemisphere swell in having a shorter period.

Data available indicate that the frequency of occurrence of these storms is quite low. Six cyclones annually was the average for 30 years determined by Nicholson, et al. (1946) with an extreme of 14 for a single year. September is the month when most of these occur. By the time the storms reach the latitude of southern California they usually have utilized a great deal of their initial energy and the surface winds are not of the high velocities often associated with hurricanes.

Although data were incomplete, Nicholson, et al. hazarded the following comments concerning this source of swell: "Over a period of forty years only one typhoon, that of September 1939, entered southern California waters with high wind velocities and caused significant damage due to wind waves. Waves from a similar storm, if and when one arrives again, will undoubtedly be the most severe affecting the area. Unfortunately, the height of the typhoon waves, the direction of their approach to the beach, and the strength and direction of the longshore currents under such conditions cannot be estimated."

Without additional data the estimate of one occurrence every four or five years cannot be modified, but the possibility should be entertained of a frequency as high as once a season. There is no indication that these waves always arrive with destructive heights. On the contrary, they will often be low.

Cold Front Passages

Two primary and three secondary meteorological patterns result in bringing onshore wind waves to Santa Monica Bay. These waves, characterized by their choppiness and short period, are always accompanied by strong winds, and since they are generated within the general area, the sheltering influence of the points, headlands, and islands is not so well marked. Because the height and period of the wind waves is a function of the wind fetch as well as the wind velocity and duration, a variation in size and period of the wind waves with the wind direction is to be expected.

Whenever the Pacific High has weakened or moved far enough south, and northwesterly flow prevails over the eastern margin of the Pacific Ocean, cold fronts originating in the Southern Gulf of Alaska may move to southern California. During the winter season this may occur several times a month bringing rain and moderate winds, in the main, first from the west and then the northwest. At times, before the frontal crossing, southwest winds may blow for a short period, generally less than a day, causing a flat sea.

As the fronts approach California, the winds and fronts move in about the same direction with the latter often traveling at approximately the same speed as the group velocity of the waves. Only rarely do the winds and waves follow a bearing of less than 270°. This means that fairly high wind waves of moderate period will enter Santa Monica Bay. Since most of the wind waves will be traveling in a southeasterly direction, they will be greatly modified along the Malibu shore.

During the months of December, January, February, and March, two to four cold front passages can be expected each month, but it is estimated that only one of these is apt to bring moderate onshore winds. In midsummer, owing to the protective influence of the Pacific High, only the strongest of these cold fronts reaches southern California, and then with much reduced activity.

Coastal Lows

Depressions may originate off the coast of California and then move northwestwardly to the continent under certain meteorological conditions. These storms may contribute swell when the low remains for a few days southwest of Los Angeles before moving northwest or moves to the mainland without crossing the bay. In either case the period will be moderate or low, probably between 8 and 10 seconds. Coastal lows may move across the area shortly after developing and before swell from the storm has had a chance to arrive. Under these conditions wind waves are generated, but not always in an onshore direction.

Thermal Lows

During the warmer months of the year an extensive interior "heat low" is situated over the arid regions of the southwestern United States. On occasions this low expands northwestward, especially if the high pressure belt moves northward, causing southern California to come under the influence of the easterlies and bringing westerly winds to Santa Monica Bay. Usually these winds are weak and can be ignored in their influence on the waves, except as they reinforce the sea breeze.

The prevailing northwesterly flow over the coast of California is often strengthened by the coincident existence of the thermal low and a strong lobe of the Pacific High extending eastward, resulting in a steep pressure gradient. Such a condition is quite conservative, and once established, is apt to prevail with little modification for days, especially in September. Whenever this situation develops, offshore winds blow.

Santanna Winds

Several times each winter a thick lens of continental polar air moves southwestward toward southern California from the interior of the continent. Strong isallobaric winds blow from the northeast coming through the passes from the desert when the air mass is dammed behind the mountains. But since these winds, although at times strong, blow from the northeast, they have little generative effect upon the waves in Santa Monica Bay.

Land and Sea Breeze Regime

Unequal heating of the earth's surface over land and over the sea causes the development of the land and sea breeze regime, which in southern California is especially well developed in the summer months. At the coast, when these conditions exist, a southwesterly wind prevails during the afternoon (the sea breeze) and a northeasterly one during the early morning (the land breeze) (Fig. 8). The sea breeze is stronger and more persistent than the land breeze. It starts some miles at sea, reaches shore about 0900 local time, and obtains its maximum extension of approximately 70 miles inland at about 1300.

Figure 8. Monthly sea conditons in San Pedro Channel.


72%
JANUARY
74%
FEBRUARY
81%
MARCH
78%
APRIL
88%
MAY
85%
JUNE
87%
JULY
91%
AUGUST
88%
SEPTEMBER
83%
OCTOBER
87%
NOVEMBER
78%
DECEMBER
SEA
(MORNING)
69%
JANUARY
65%
FEBRUARY
56%
MARCH
50%
APRIL
36%
MAY
45%
JUNE
28%
JULY
23%
AUGUST
40%
SEPTEMBER
43%
OCTOBER
55%
NOVEMBER
62%
DECEMBER
SEA
(AFTERNOON)
NUMBERS IN CENTER OF ROSE ARE THE
PERCENTAGE OF CALM TO SMOOTH SEAS
N
W
E
S
LIGHT SEA
HEAVY SEA
MODERATE SEA

Experience indicates that waves generated by sea breezes have breaking heights averaging about 2 feet and periods of about 5 seconds. They should reach their maximum development at about 1500 or 1600 hours. Although some information can be obtained on the fetches, durations, and velocities of sea breeze situations, it is difficult and probably unwise to interpret these data. In theory winds have to obtain an average velocity of about 10 knots before they are able to exert sufficient tractive force on the water surface to start the growth of waves. Sea breezes, from observation, generally have a velocity of about this order of magnitude.

WATER TEMPERATURE

Methods

Temperature data have been collected using two methods. The first is surveys of the area accomplished by traversing a network of stations at cruising speeds making bathythermograph casts at short intervals along each traverse line. In this way it is possible to obtain water temperatures to a depth of 200 feet throughout the bay in six or seven hours.

The second method consisted of occupying a grid of hydrographic stations and obtaining salinities as well as temperatures at various depths in the water column using reversing thermometers and Nansen bottles, or at the surface by bucket samples.

The bathythermograph grid is best adapted to a detailed study of temperature conditions. Hydrographic stations are required to obtain data on the various water masses and types.

Both methods are necessary parts of a complete survey.

Additional data were available from surf temperature reports of the Los Angeles County Life Guard Station at Venice, and from similar records of the U. S. Coast and Geodetic Survey at Santa Monica Harbor. For adjacent offshore areas, temperatures and salinities at various depths have been taken by the Scripps Institution of Oceanography, but their stations in most cases were located outside the area of the present investigation. The staff of the Los Angeles City Bureau of Sanitation also has collected data in the bay which are tabulated in the reports of that organization.

Thermoclines and Gradients

For the purposes of this report, thermoclines and gradients have been separated on the basis of their characteristic appearance in bathythermograms. In general, if a temperature curve changes abruptly in slope below a nearly isothermal surface layer, thus forming a sharp discontinuity or boundary, and the difference in temperature is relatively large, it has been termed a thermocline. A smooth or even an intermittent change, but without a marked break at any depth has been termed a thermal gradient. While this is a rough, qualitative distinction, it is adequate for the purpose at hand.

Thermoclines and gradients were best developed when the surface waters were warmed in the spring and summer. They were least prominent during the late fall and winter months when surface temperatures were reduced.

Inversions were characteristically present in thermograms from the outfall areas. Evidently the turbulent nature of the boil is the primary cause of these thermal variations. As the warm effluent leaves the pipe it mixes with bottom water and moves toward the surface as a more or less fractured mass. A bathythermograph lowered into the area of an outfall will thus intercept alternate zones of poorly mixed, unstable water. Typical inversions at the Hyperion outfall were present on July 20, 1956. Figure 9 shows the vertical temperature profile along a line extending from the boil to a distance of 6 miles from shore. Figure 10 is a detailed representation of the area near the boil. The deflection of the 54° to 61°F isotherms reflects the entrapment of cold bottom water by the rising boil and its subsequent rise toward the surface.

Inversions were encountered frequently in the southern reaches of the bay and in the offshore portions of the north and north-central areas. Here the inversions appeared to be due to a horizontal overlapping of different water types. These warmer bodies of water must have had a sufficiently high salinity to make them stable under such circumstances. In all cases the inversions were of small magnitude and the level at which they occurred was well above the major boundary between the warm surface layer and the colder subsurface water.

A peculiar inversion was encountered in only two or three instances near the bottom of the central bay shelf. There is no obvious explanation for such a warm layer in that area and at that depth. In any event, it is not of major significance in the thermal structure of the bay.

Figure 9. Vertical water temperature profile in Santa Monica Bay extending seaward from Hyperion boil, July 20, 1955.

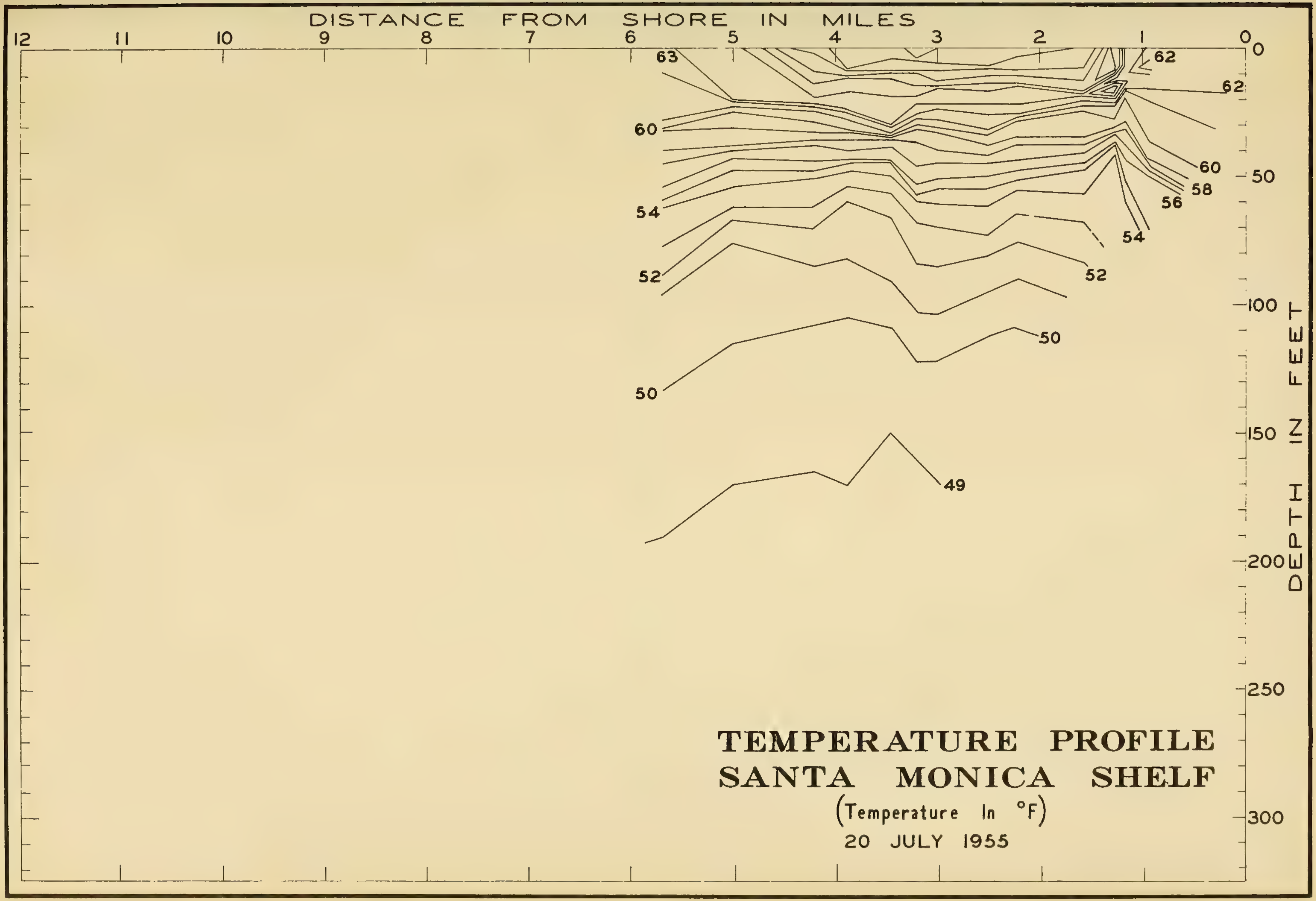
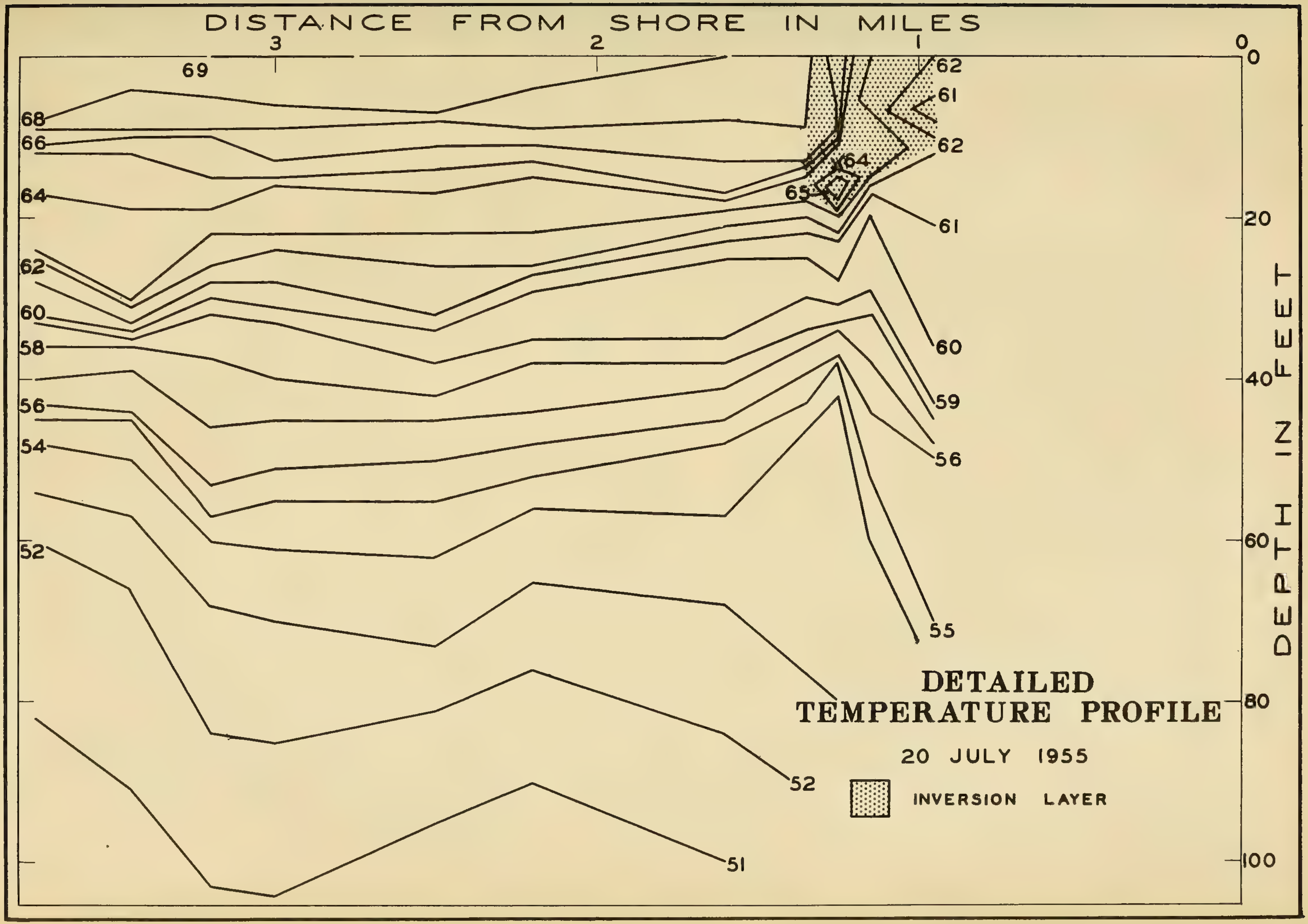

DISTANCE FROM SHORE IN MILES
12
11
10
9
8
7
6
5
4
3
2
1
0
DEPTH IN FEET
0
50
100
150
200
250
300
63
62
62
60
60
58
56
54
54
52
52
50
50
49
TEMPERATURE PROFILE
SANTA MONICA SHELF
(Temperature In °F)
20 JULY 1955

Figure 10. Detailed water temperature profile, July 20, 1955.



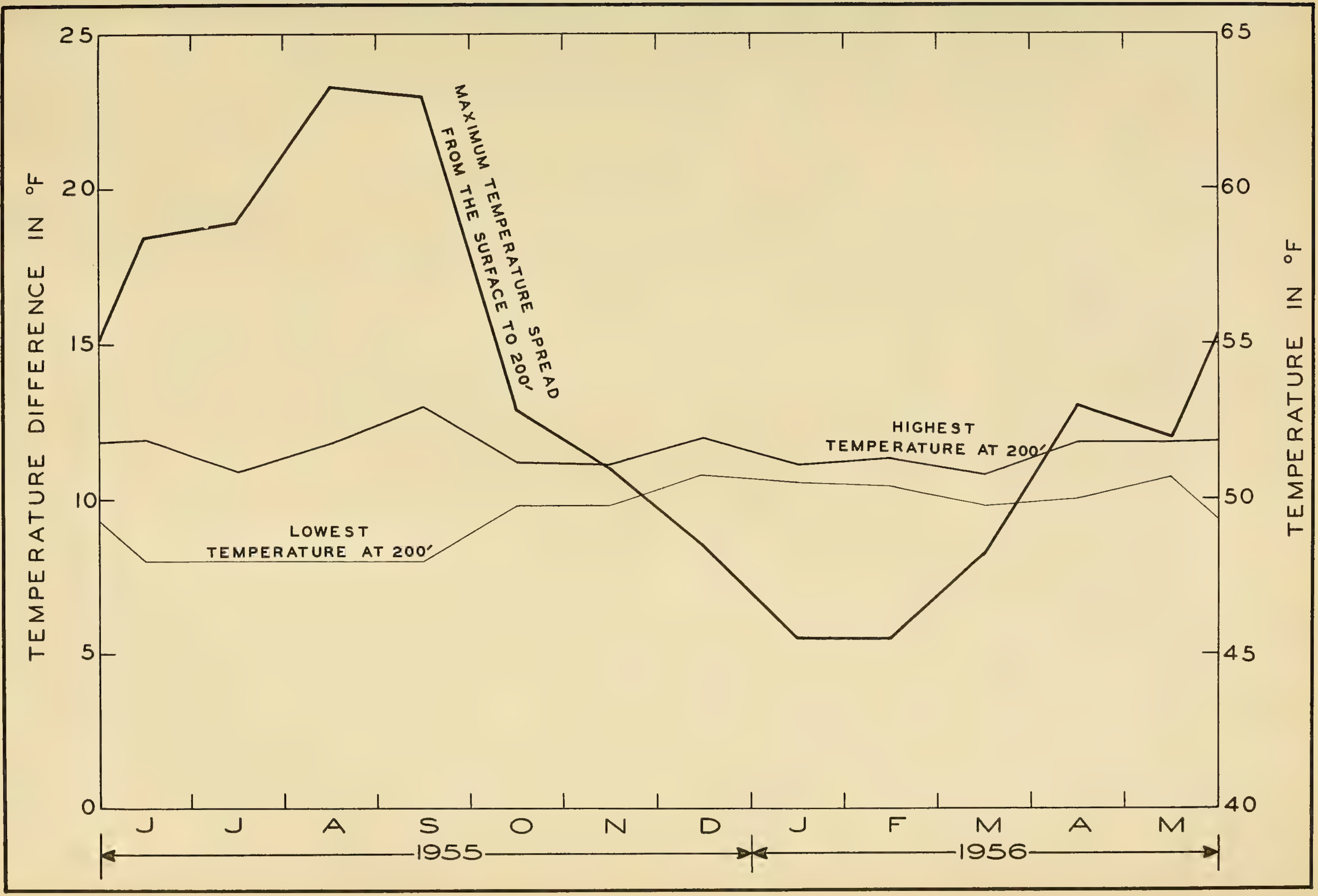
DISTANCE FROM SHORE IN MILES
DEPTH IN FEET
DETAILED TEMPERATURE PROFILE
20 JULY 1955
INVERSION LAYER

The possible role of the thermocline as a density barrier to the rise of effluent-sea water mixtures is discussed in the section on dilution. It would appear from field observations of bacteria, nutrients, and turbidity in the neighborhood of outfalls that the main importance of these thermal and density boundaries lies in their effect on the position of turbid layers following the initial rise of the effluent discharge toward the surface. Figure 11 shows the limiting ranges of water temperature in 200 feet of shelf water at which suppression of the rising effluent may occur.

Classification of Water Masses and Types

It is convenient, when dealing with ocean water, to plot temperature against salinity, the resulting curve being called a T-S curve. A water mass is a body of water having certain temperature and salinity relationships and is defined by a T-S curve. The whole body of water lying over the Santa Monica Bay shelf is an example of such a water mass. A water type, on the other hand, is defined by a single temperature and a single salinity value. Within a restricted area the horizontal distribution of water types can be represented by surfaces containing all points in a water mass having these singular characteristics. In the special case of the Santa Monica shelf where the salinities are nearly uniform, such surfaces will approximately correspond to isothermal surfaces. Ordinarily, water mass and water type analyses are not made for waters near the surface or in shallow areas. However, in this case they have proved useful. In previous reports the two basic terms sometimes

Figure 11. Maximum and minimum water temperatures at 200 feet, and maximum temperature differences between surface and 200 feet, Santa Monica Bay, 1955-56.



25
20
15
10
5
0
TEMPERATURE DIFFERENCE IN °F
65
60
55
50
45
40
TEMPERATURE IN °F
MAXIMUM TEMPERATURE SPREAD FROM THE SURFACE TO 200′
HIGHEST TEMPERATURE AT 200′
LOWEST TEMPERATURE AT 200′
J J A S O N D J F M A M
1955
1956

have been used interchangeably. For this reason and also to avoid confusion with the terms used in dealing with the open ocean, the term <u>water unit</u> is introduced, better to describe the detailed classification of the water in Santa Monica Bay. Where further subdivision is necessary, the term <u>sub-unit</u> will be used (Table I).

The principal body of water which overlies the Santa Monica shelf has been named the Shelf Water Mass. Its characteristics are an essentially uniform salinity of about 33.5 o/oo and temperatures ranging from 48° to 73°F, depending on season and depth. Its character and T-S relationships are shown in Figure 12, which is a cumulative temperature-salinity diagram for the waters of Santa Monica Bay.

Below the Shelf Water Mass lies a layer of somewhat different characteristics, here named the Slope Water Mass. This water ranges in temperature from 46° to 50°F, and in salinity from 33.6 o/oo to 34.3 o/oo.

The deepest water present in the vicinity is here termed the Basin Water Mass. It exhibits an essentially uniform salinity below the depth of the sill of the Santa Monica Basin. This water mass is characterized by an average temperature of 43°F and salinity of 34.3 o/oo.

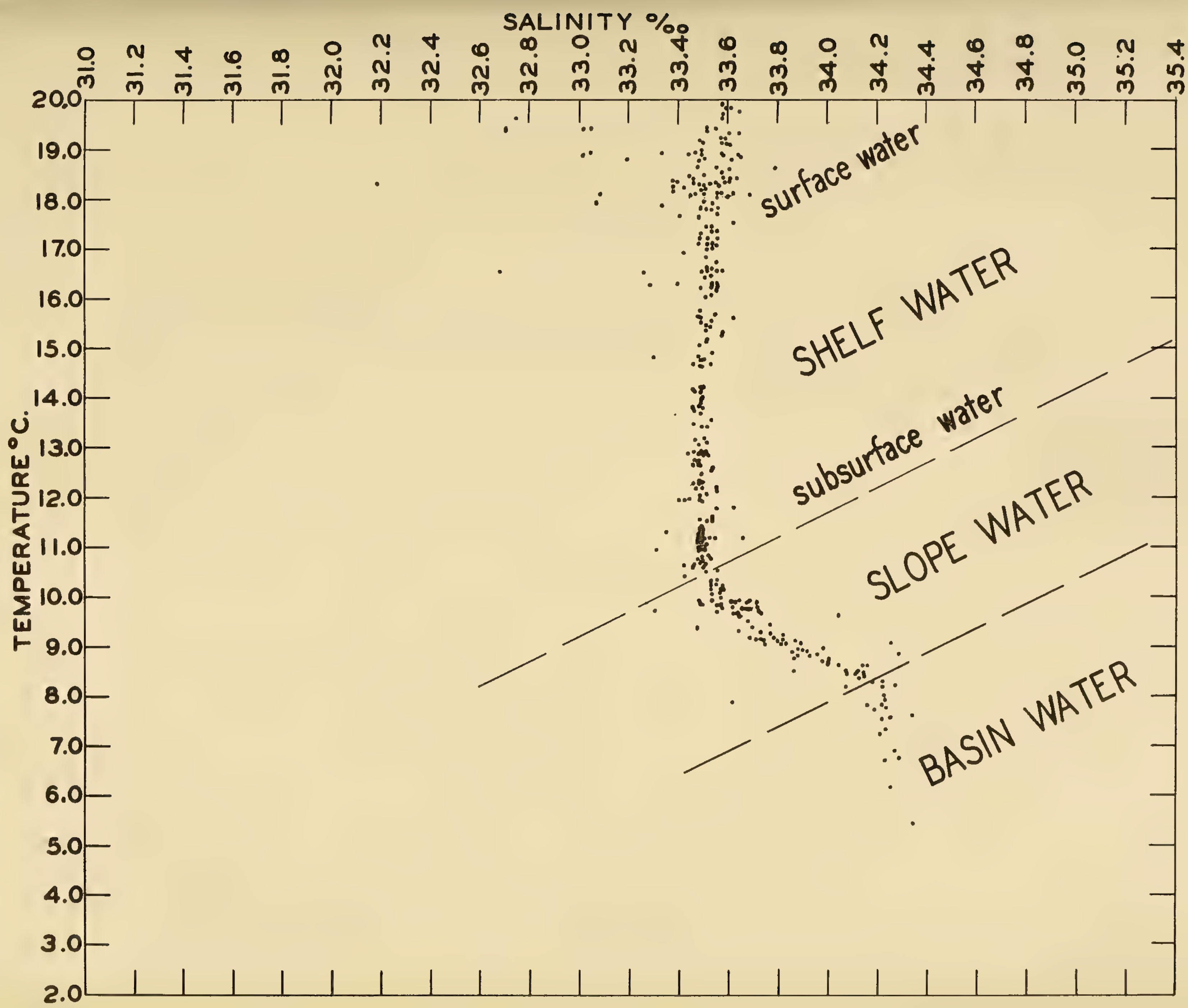
Within the Shelf Water Mass are two distinct water units, separated primarily by temperature discontinuities or thermoclines. The Surface Water Unit includes the layer in which the greatest seasonal temperature changes occur. It lies above the thermocline and above such gradients in salinity as do exist in the shelf water. The more uniform lower portion

TABLE I

Water Classification System

Classification	Example
Water Mass	Shelf Water Mass
Water Unit	Shelf Surface Water Shelf Subsurface Water
Water Subunits	Sewage Field
Water Type	Isothermal Temperature Surface

Figure 12. Temperature-salinity relationships in Santa Monica Bay, 1955-56.


SALINITY ‰
TEMPERATURE °C.
surface water
SHELF WATER
subsurface water
SLOPE WATER
BASIN WATER

of the Shelf Water Mass comprises the Subsurface Water Unit. It is considered to be characteristic of the Shelf Water Mass proper, and its upper boundary lies at the thermocline. At this level more or less well-defined temperature discontinuities are present throughout the year. Although they vary greatly in the magnitude of the temperature change, there is usually no difficulty in defining the boundary between the Surface and Subsurface Water Units.

Within the Surface Water Unit, a Sewage Field Sub-unit has been defined, characterized by high temperatures and low salinities.

Annual Ranges in Temperature

The limits of the temperature range within the bay for increments of ten feet of depth are shown in Figure 13. This represents the yearly range at each of these depths over the entire bay. It should be noted that in particular areas of the bay the ranges are much smaller; for example, the temperatures at particular localities, or at depths of 100 feet or more, probably change less than 3°F.

The Surface Water Unit is the one of greatest temperature change because of seasonal variations in solar heating, evaporation, and other factors (Fig. 14). During the summer and early fall the inshore surface water may reach temperatures of 72°F. In the winter the same area may have a surface temperature of 58°F. In the central shelf area, summer temperatures may approach 67°F and winter temperatures, 56°F. For the bay as a whole, surface temperatures may range over

Figure 13. Limits of water temperature range for 10-foot intervals of depth, Santa Monica Bay, 1955-56.

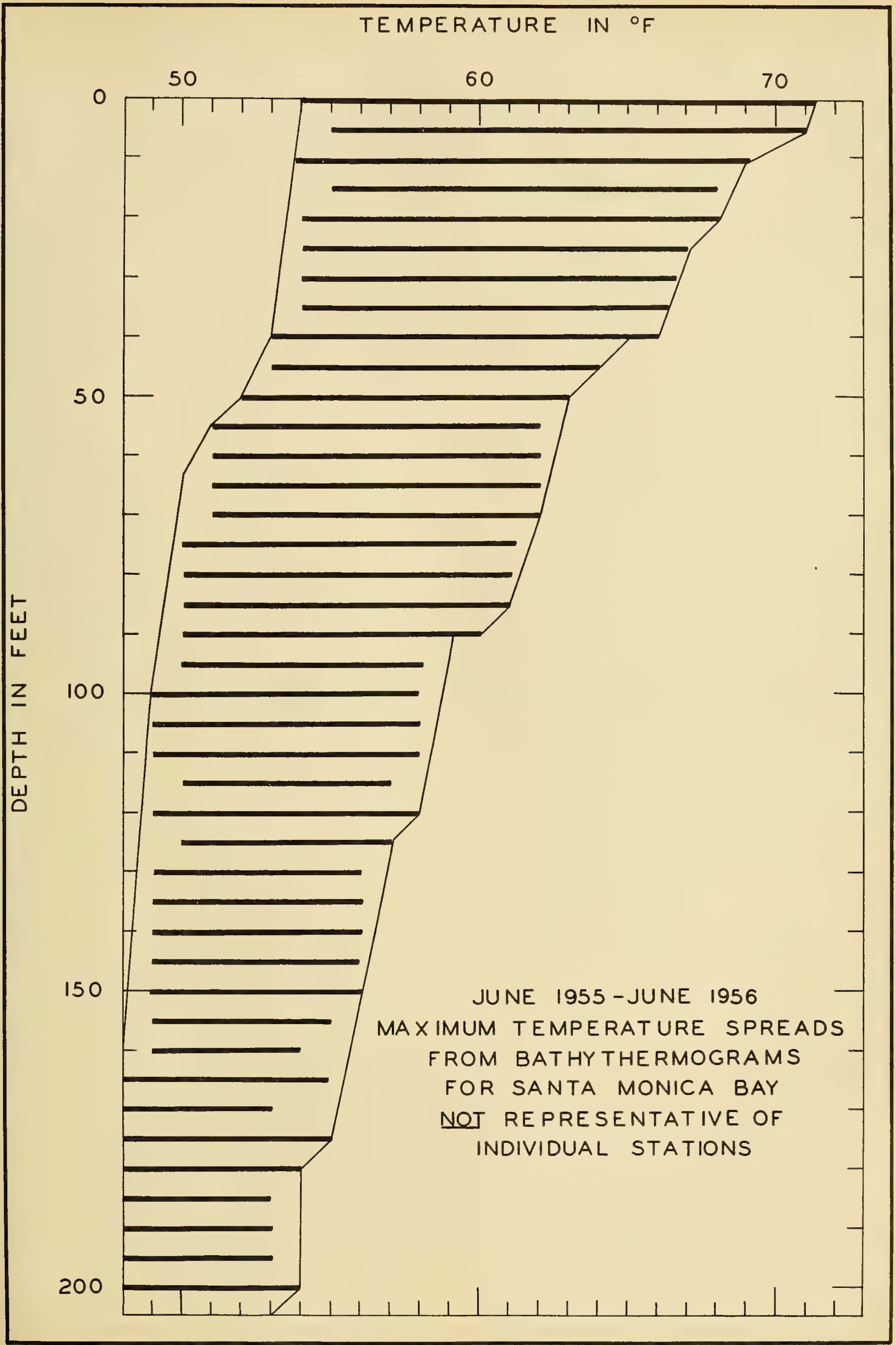
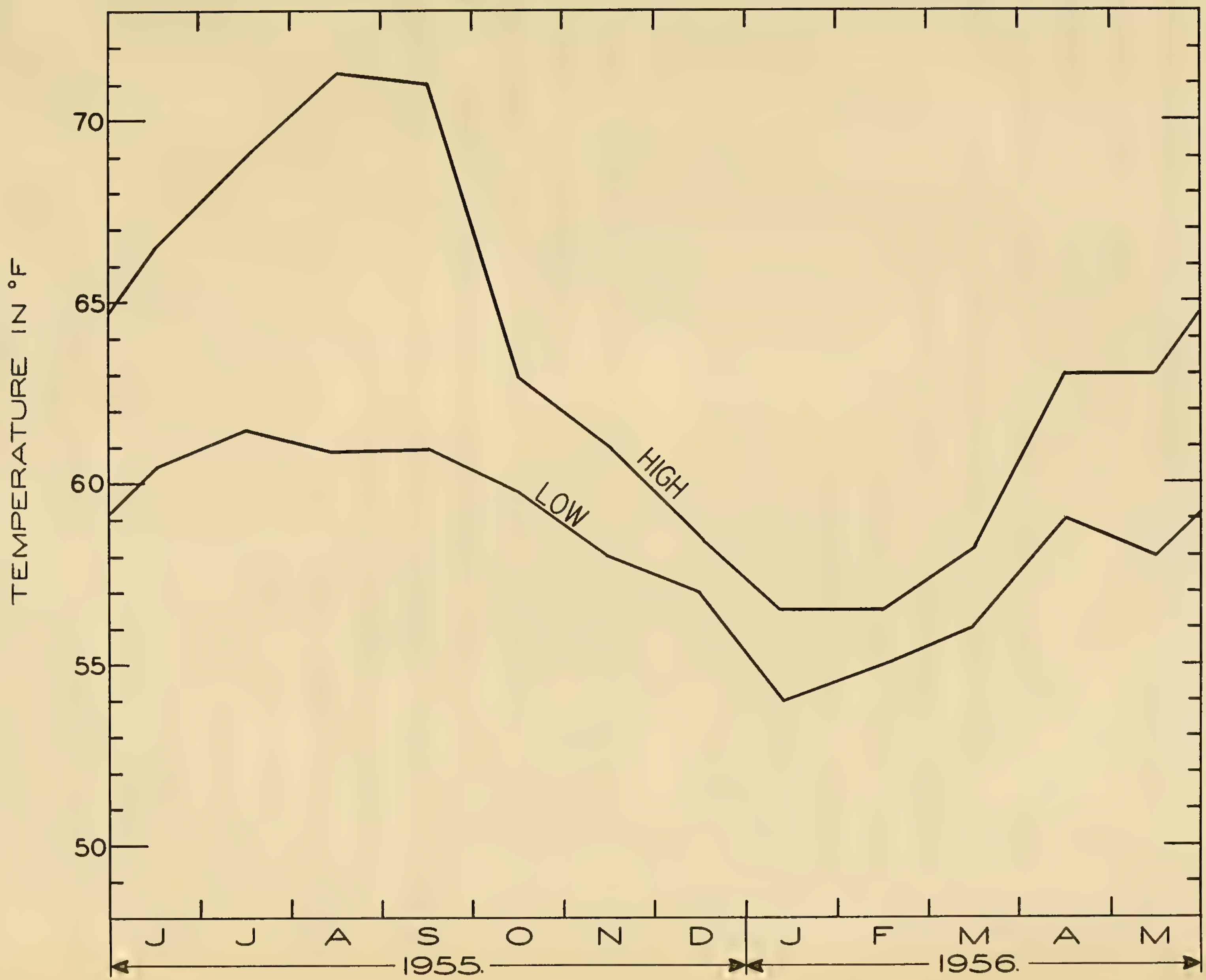

TEMPERATURE IN °F
50
60
70
0
50
100
150
200
DEPTH IN FEET
JUNE 1955 - JUNE 1956
MAXIMUM TEMPERATURE SPREADS
FROM BATHYTHERMOGRAMS
FOR SANTA MONICA BAY
NOT REPRESENTATIVE OF
INDIVIDUAL STATIONS

Figure 14. Maximum and minimum surface water temperatures.

SURFACE TEMPERATURES

SANTA MONICA BAY, CALIFORNIA



$20^{\circ}F$, but as noted previously, the spread in temperature in any given locality never approaches this extreme value. A reasonable local figure for seasonal differences would be of the order of 12° to $15^{\circ}F$.

As a thermal entity, the Sewage Field Sub-unit is clearly defined on charts of surface temperature in the winter, and it appears to occupy a relatively small area around the outfall. In the summer, it is not as well defined because solar heating has raised the temperature of the surrounding areas to nearly that of the sewage field. In summer, therefore, surface temperature charts may not be adequate to delineate the extent and position of the field.

The Subsurface Water Unit is of relatively constant temperature, the maximum range within the bay as a whole being no more than $6^{\circ}F$. The most typical temperature seems to be $53^{\circ}F$, and the greatest variations appear to be due to the intrusion of water of slightly different thermal characteristics.

Figures 11 and 13 illustrate the differences in temperature between the surface and 200 feet in shelf water as a whole. The maximum and minimum temperatures at 200 feet are also indicated. The differences are greatest in those months when the surface temperatures are highest. It is evident that density distributions must follow the same seasonal pattern, and that the greatest temperature drops at thermoclines or gradients occur in the summer and early fall months coincident with periods of greatest surface temperatures.

The Seasonal Character of Shelf Water Units

The temperature characteristics of the various shelf water elements from June 1955 to June 1956 are shown in Figures 15 to 21. Only the vertical relationships of the units and subunits have been scaled. Horizontal dimensions have been ignored for simplicity. In the following discussion only a few representative temperature distributions are described in detail.

June 1955

In June 1955 a thermal boundary existed between the Surface and Subsurface Water Units, consisting of successive layers of nearly isothermal water and forming a series of distinct steps. The Surface Unit had a temperature range of from 60°F to 66°F inshore, and was subdivided into at least two subunits (Fig. 15).

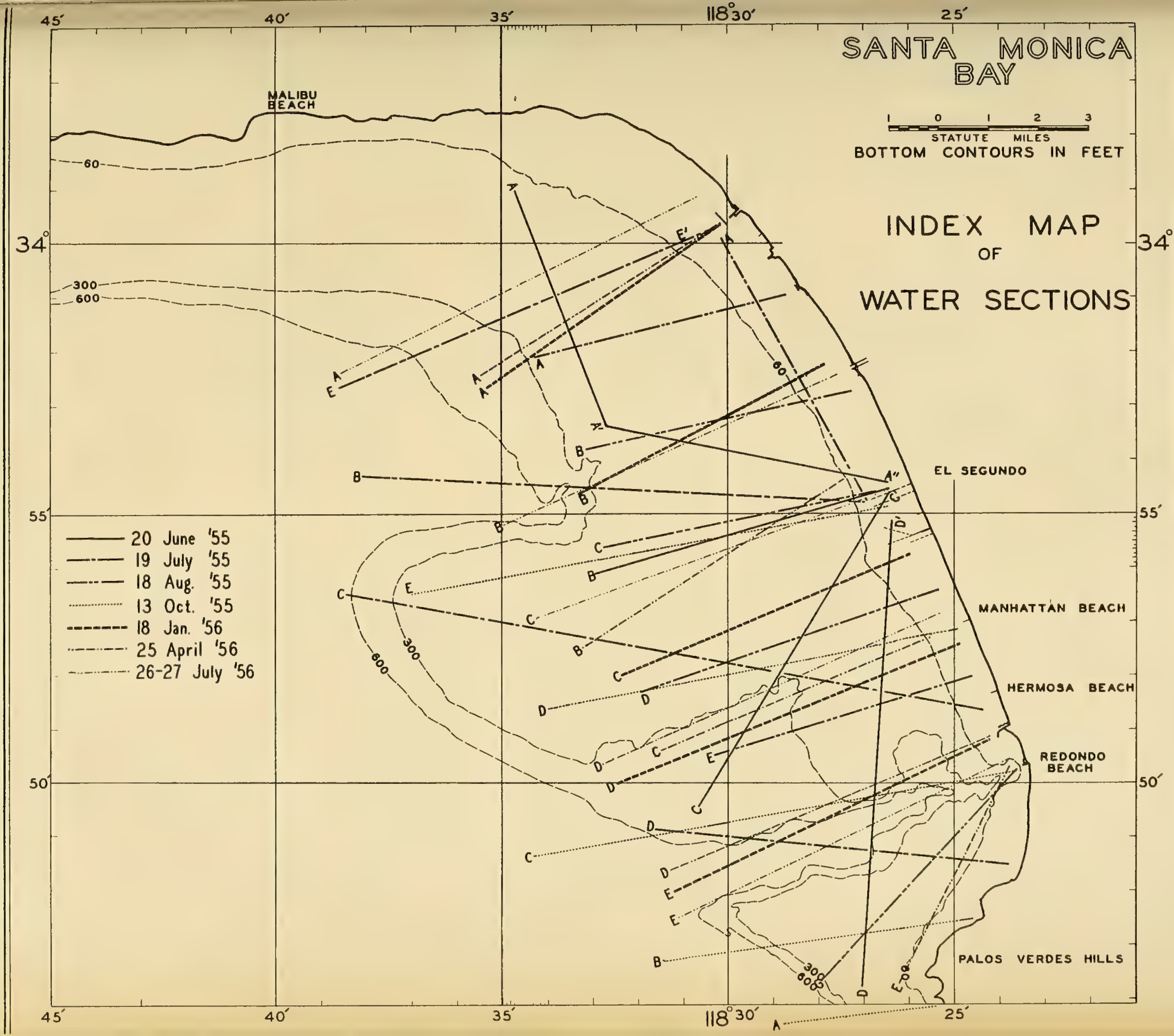
Subunit 1, which covered the greatest area, had a temperature range of from 60° to 62° and an average thickness of approximately 20 feet. It reached a maximum thickness of 50 feet in the central portions of the bay. This water was probably moved inshore by the prevailing winds where it mixed partially with underlying water and partially with nearshore water. Subsequently, it was overlapped by the warm nearshore Surface Unit in the central shore margins of the bay.

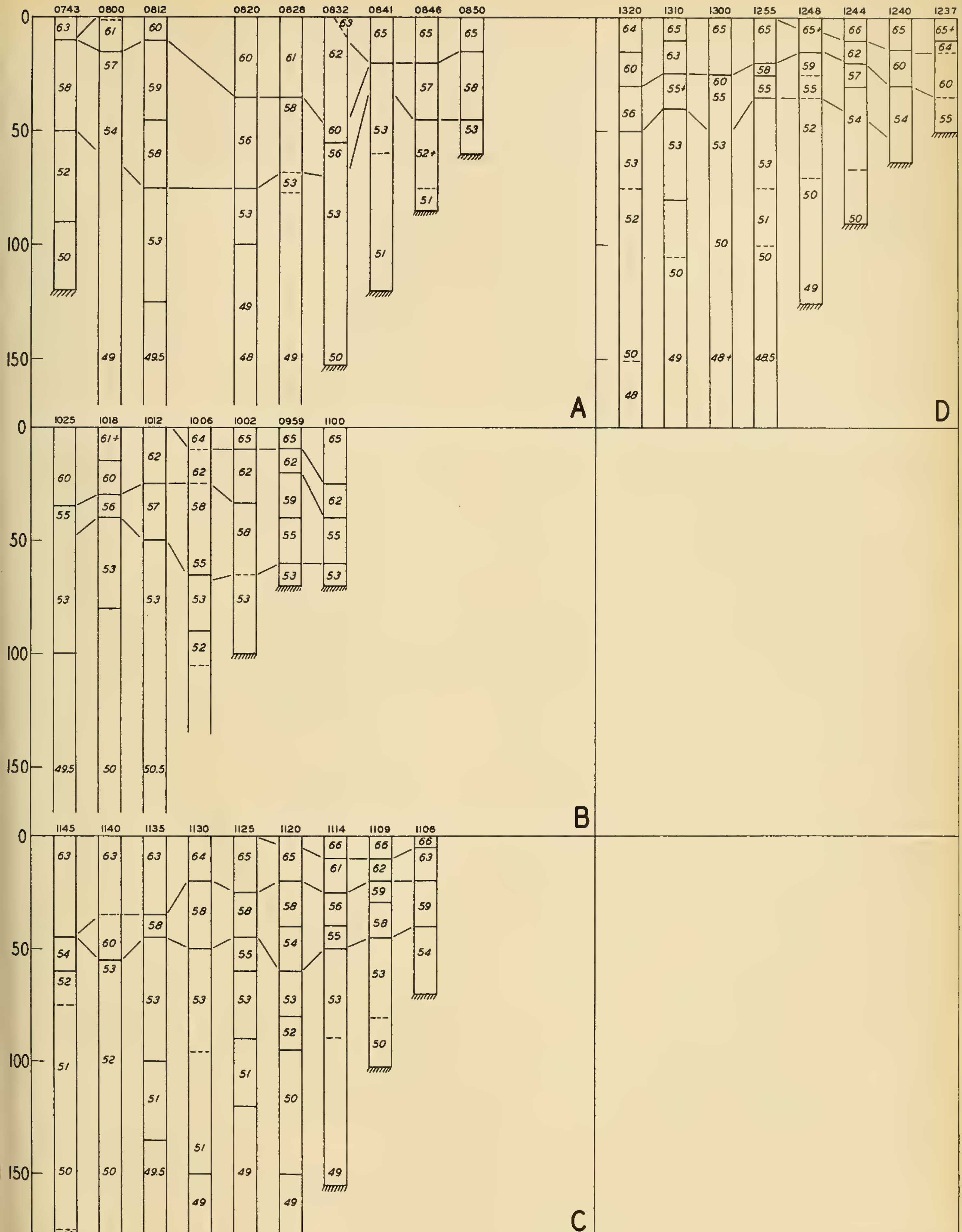
The nearshore warm layer (Subunit 2) had a temperature range of from 64° to 66°, which was apparently the result of increased heating in shallow water and of heat contributed by effluent and warm water discharge from the Edison Company Steam

Figure 15.

A. Index map of temperature profiles in Santa Monica Bay.

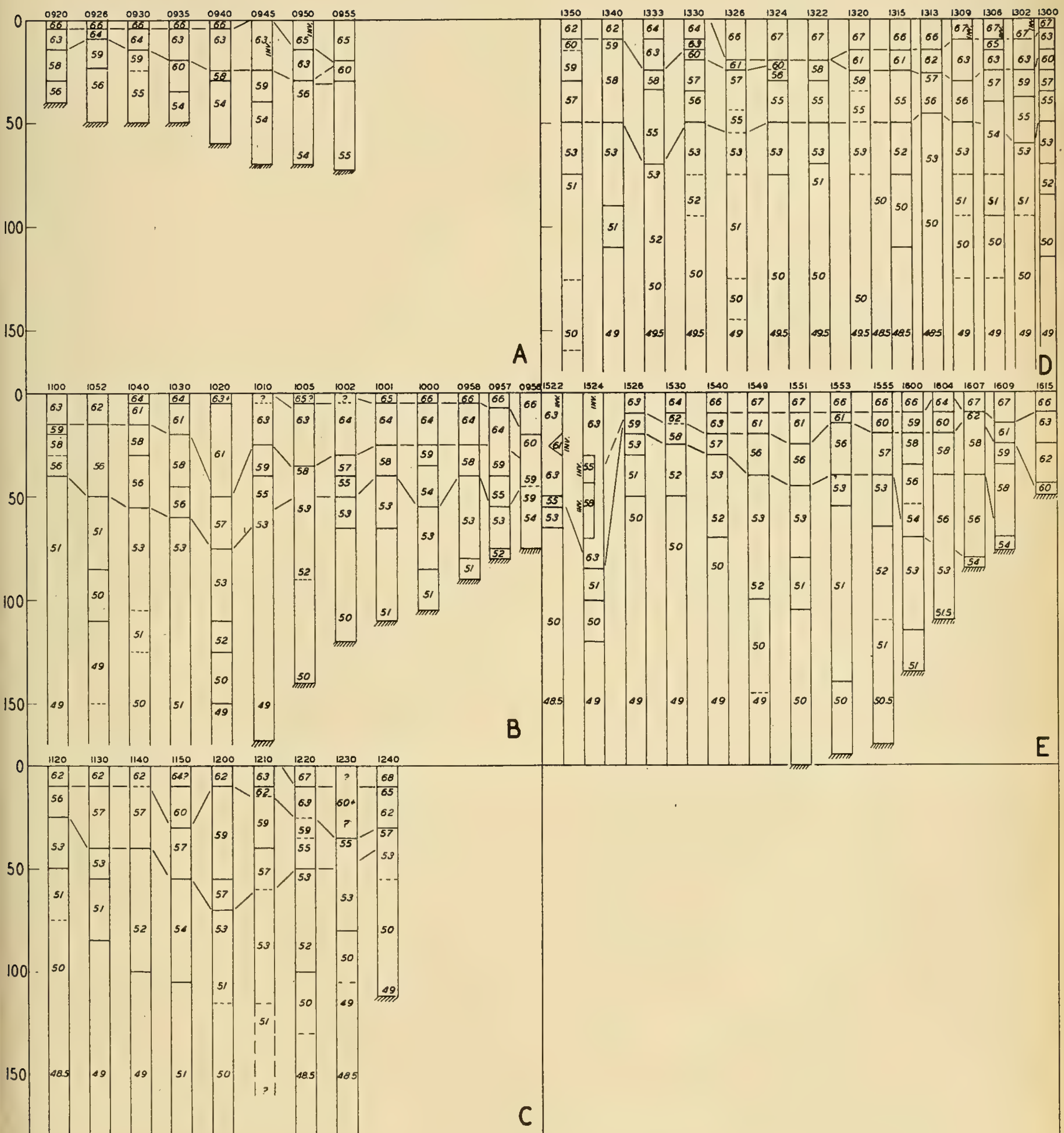
B. Vertical temperature distribution, June 20, 1955


SANTA MONICA BAY
INDEX MAP OF WATER SECTIONS
STATUTE MILES
BOTTOM CONTOURS IN FEET
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
20 June '55
19 July '55
18 Aug. '55
13 Oct. '55
18 Jan. '56
25 April '56
26-27 July '56
118°30′
34°
55′
50′
45′
40′
35′
25′


A
0743 0800 0812 0820 0828 0832 0841 0846 0850
B
1025 1018 1012 1006 1002 0959 1100
C
1145 1140 1135 1130 1125 1120 1114 1109 1106
D
1320 1310 1300 1255 1248 1244 1240 1237
0
50
100
150

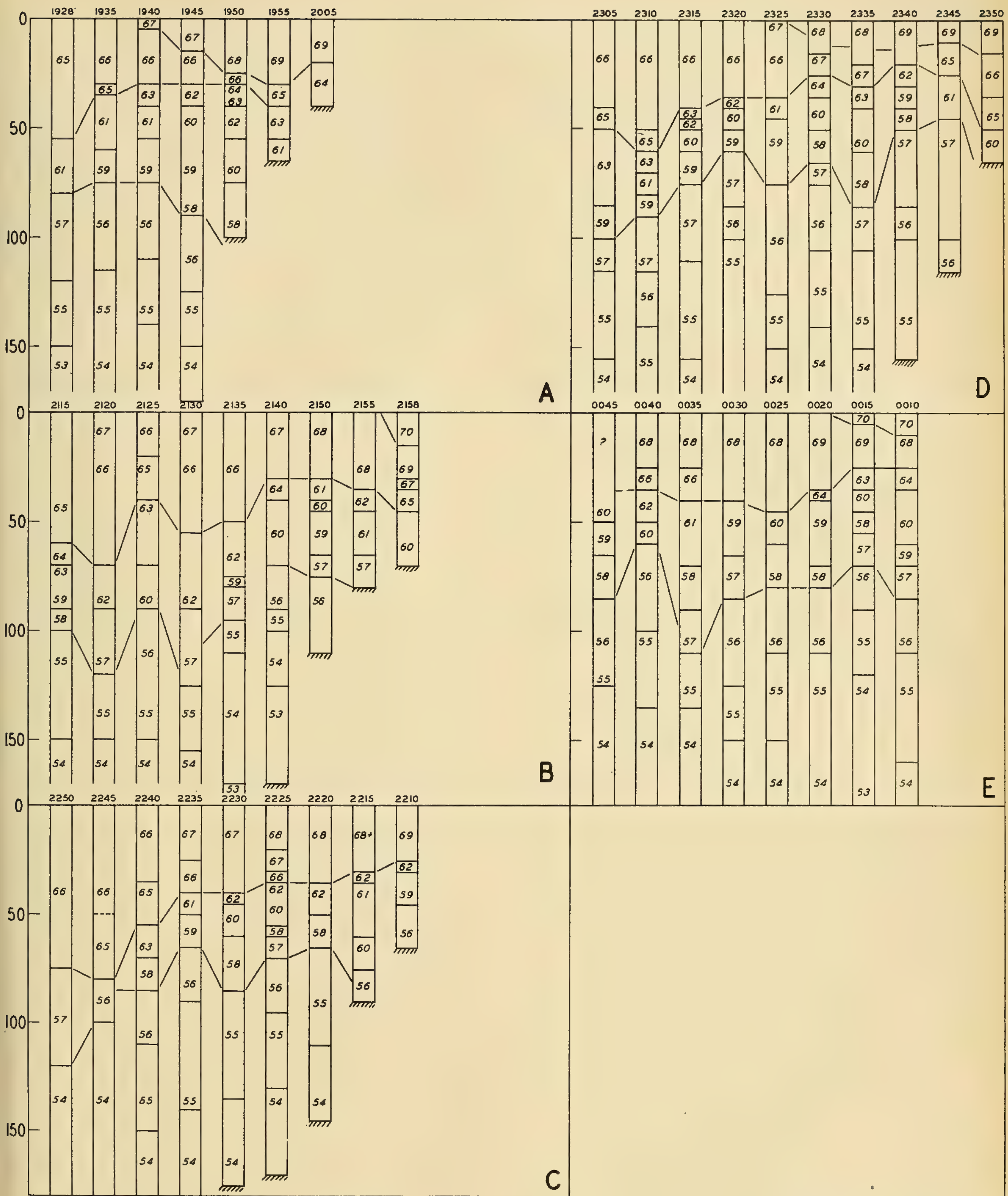
20 JUNE

Figure 16. Vertical temperature distribution,
July 19, 1955



19 JULY '55

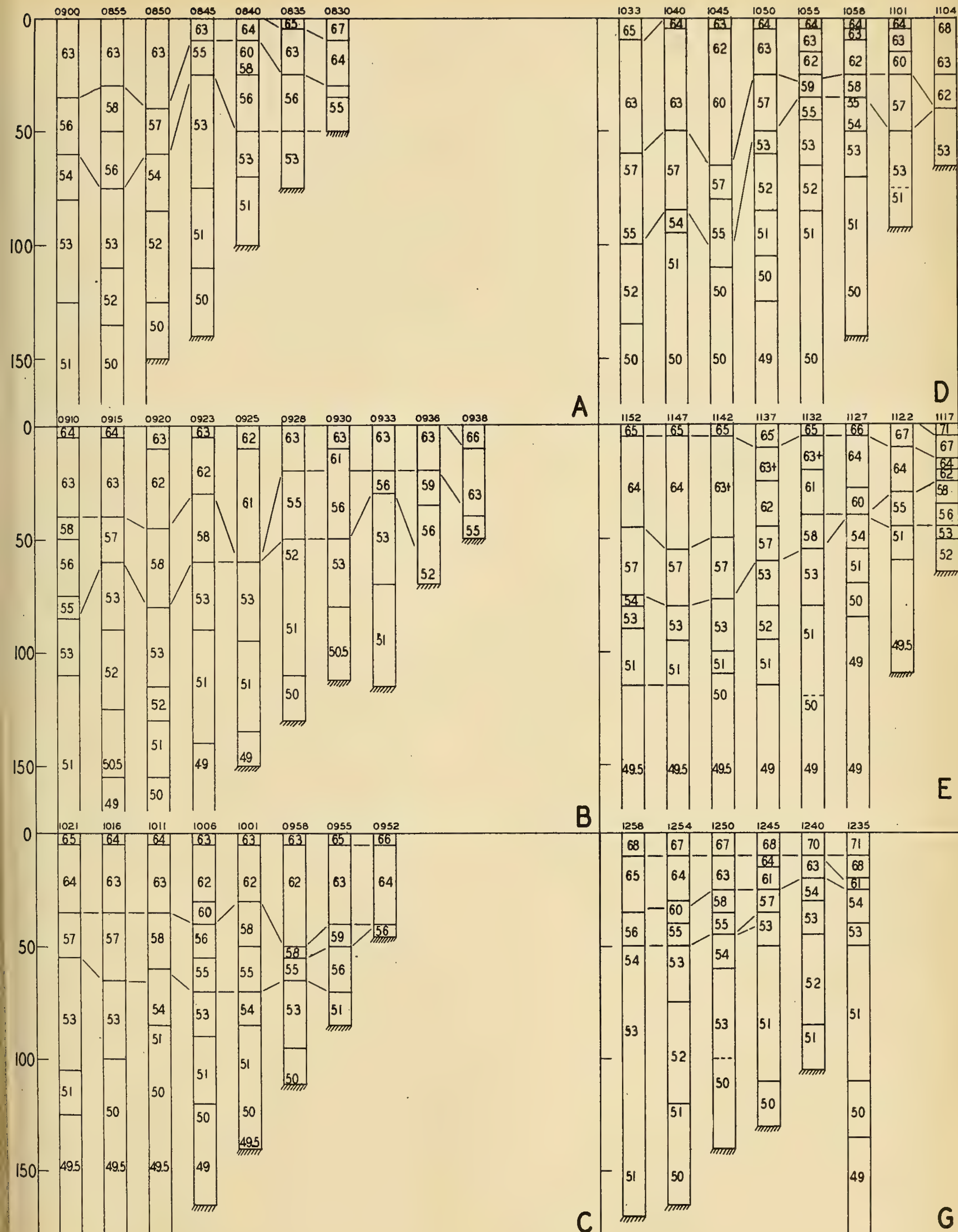
Figure 17. Vertical temperature distribution,
July 26-27, 1956



A
1928 1935 1940 1945 1950 1955 2005
B
2115 2120 2125 2130 2135 2140 2150 2155 2158
C
2250 2245 2240 2235 2230 2225 2220 2215 2210
D
2305 2310 2315 2320 2325 2330 2335 2340 2345 2350
E
0045 0040 0035 0030 0025 0020 0015 0010
0
50
100
150

26 - 27 JULY '56

Figure 18. Vertical temperature distribution, August 18, 1955


0900 0855 0850 0845 0840 0835 0830
1033 1040 1045 1050 1055 1058 1101 1104
0910 0915 0920 0923 0925 0928 0930 0933 0936 0938
1152 1147 1142 1137 1132 1127 1122 1117
1021 1016 1011 1006 1001 0958 0955 0952
1258 1254 1250 1245 1240 1235
0
50
100
150
A
B
C
D
E
G

18 AUGUST '55

Figure 19. Vertical temperature distribution,
October 13, 1955

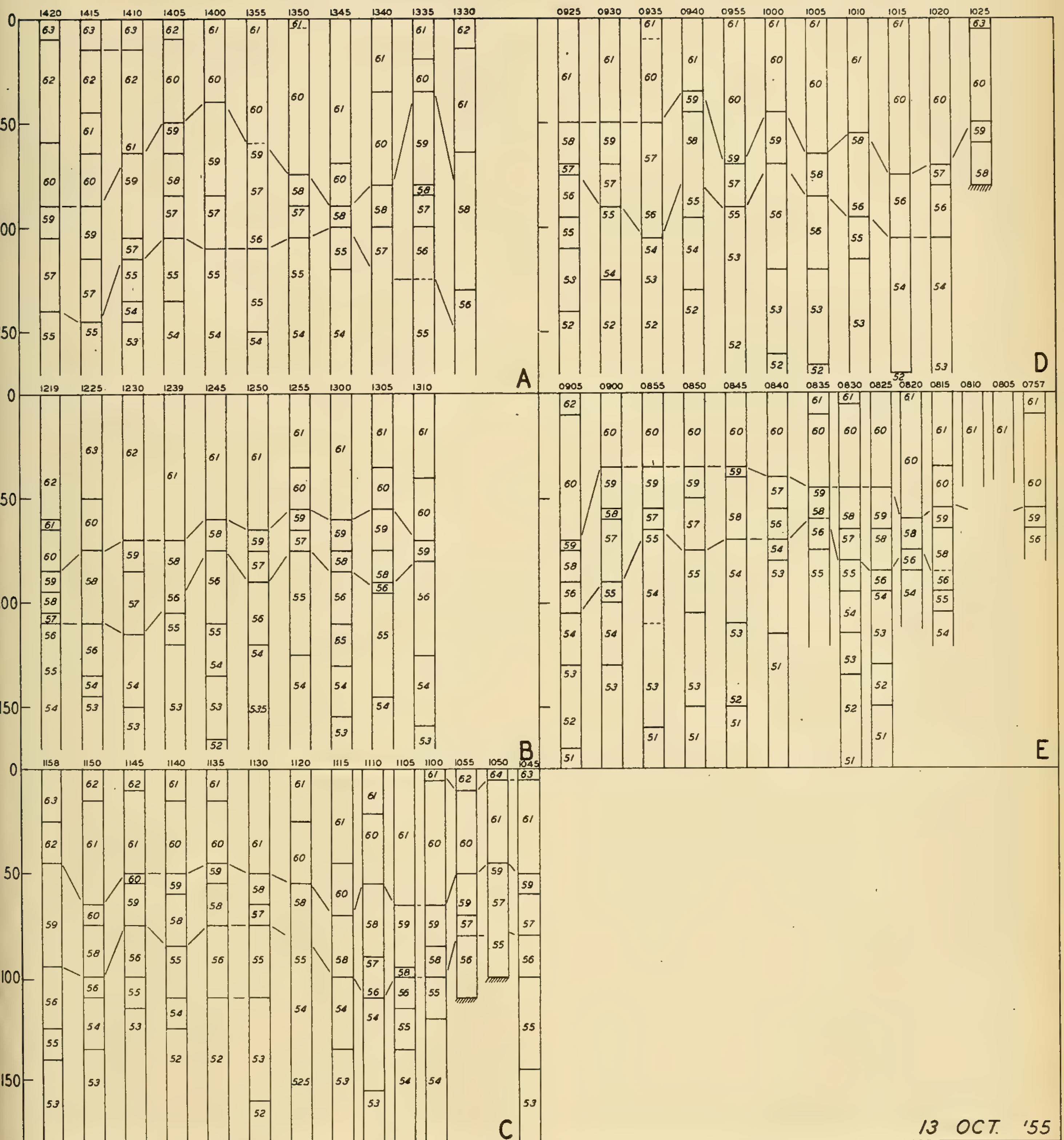
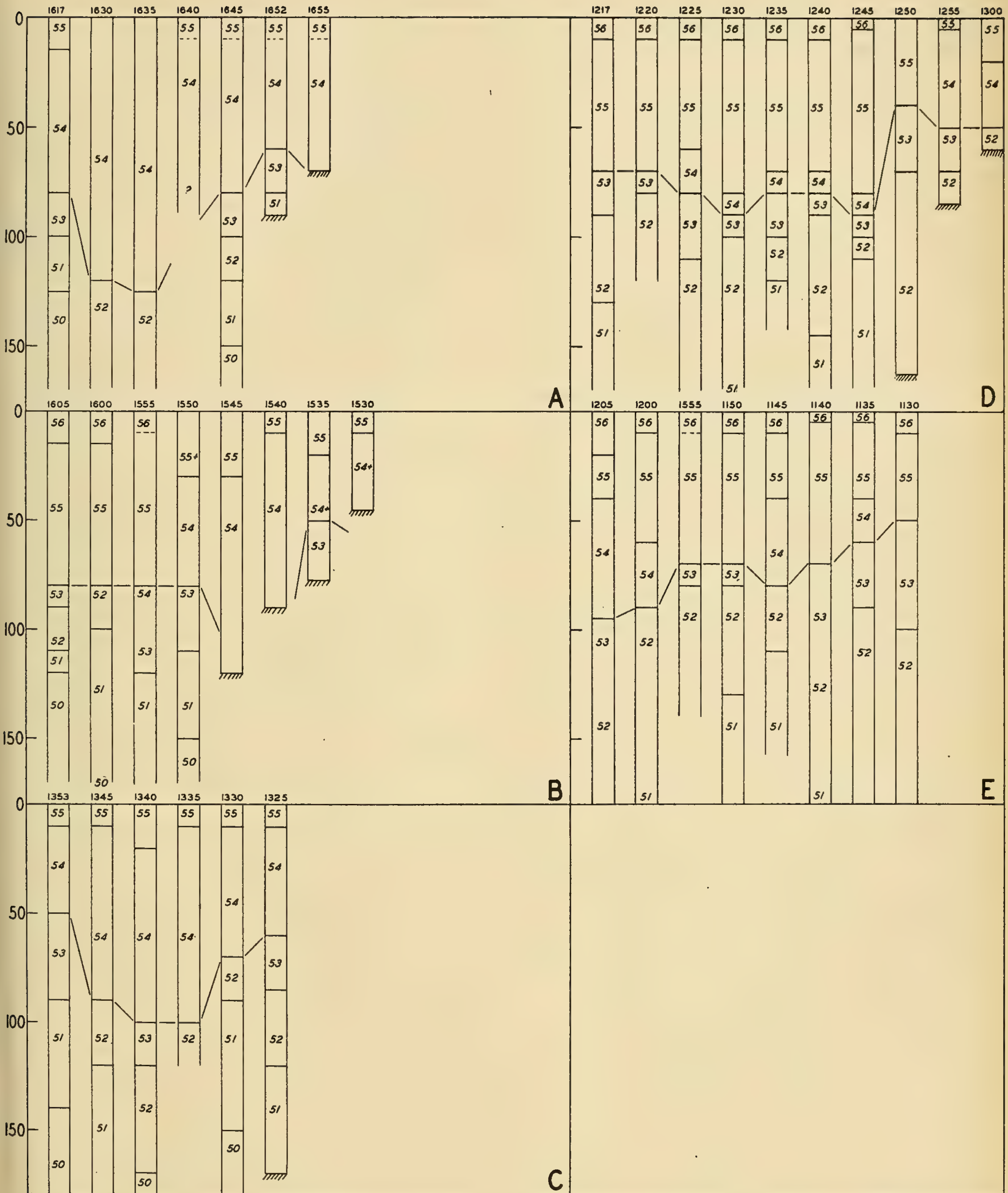
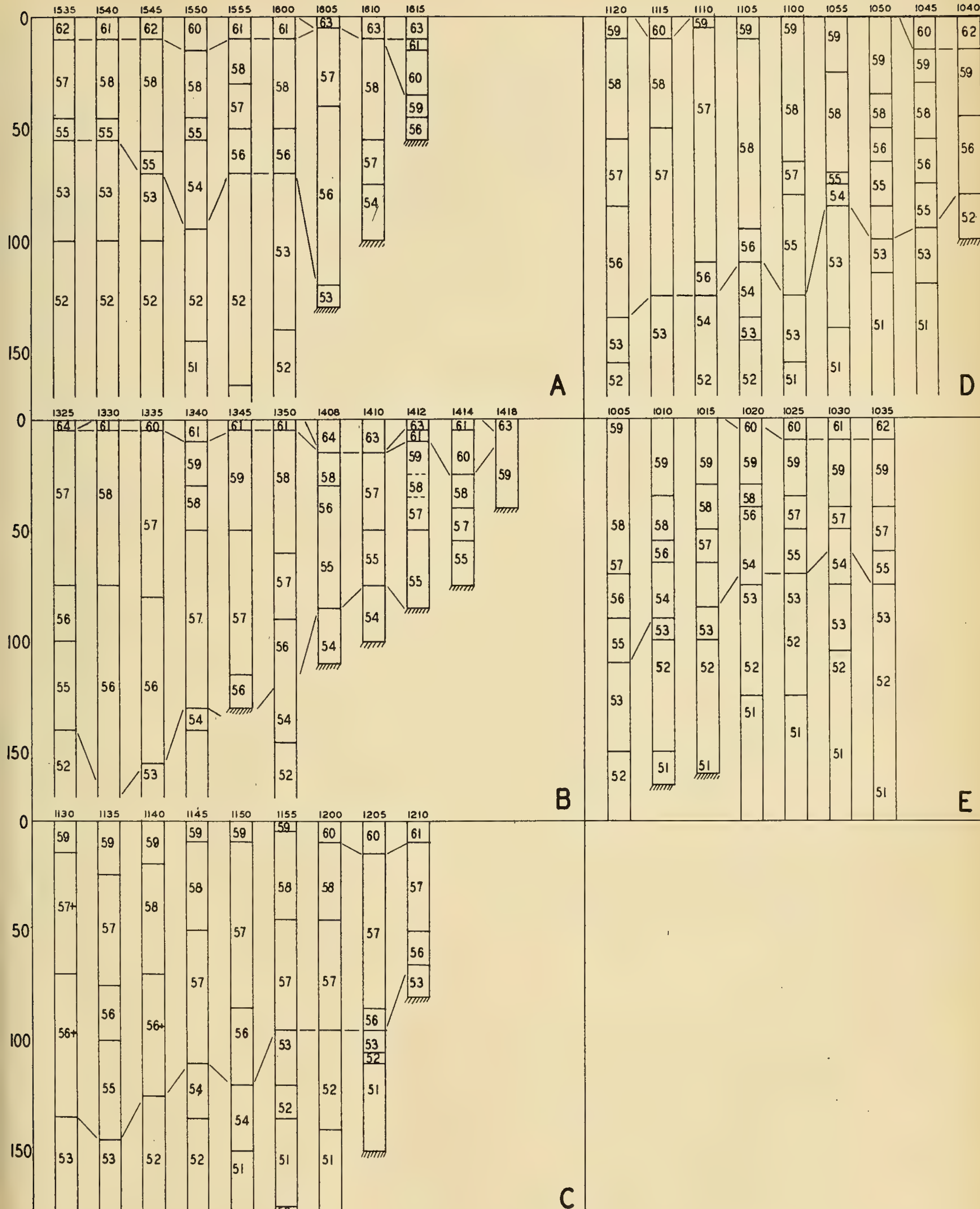

A
B
C
D
E
13 OCT. '55

Figure 20. Vertical temperature distribution,
January 18, 1956


A
1617 1630 1635 1640 1645 1652 1655
B
1605 1600 1555 1550 1545 1540 1535 1530
C
1353 1345 1340 1335 1330 1325
D
1217 1220 1225 1230 1235 1240 1245 1250 1255 1300
E
1205 1200 1555 1150 1145 1140 1135 1130
0
50
100
150

18 JAN. '56

Figure 21. Vertical temperature distribution,
April 25, 1956


1535 1540 1545 1550 1555 1600 1605 1610 1615
A
1120 1115 1110 1105 1100 1055 1050 1045 1040
D
1325 1330 1335 1340 1345 1350 1408 1410 1412 1414 1418
B
1005 1010 1015 1020 1025 1030 1035
E
1130 1135 1140 1145 1150 1155 1200 1205 1210
C
0
50
100
150

25 APRIL '56

Plant. Part of the increased temperature may also have been due to the formation of slow moving gyrals in the southern portion of the bay and a consequent increase in local water temperature from solar heating alone.

Below these two subunits were several patches of water of varying temperature that form an intermediate zone between the Surface and Subsurface Units. These were sufficiently developed to be treated as more than a transitional subunit.

The Subsurface Water Unit was composed of several broad strata ranging downward in temperature from 53° to 48°F. The main temperature differential between surface and subsurface water amounted to about 10° at an average depth of 55 feet. The subsurface water gave some indication of progressively higher temperatures in an inshore direction, perhaps indicating motion of water at most depths over the shelf toward shore. It is interesting to note that the coldest water and the warmest water occurred together during the summer months. This cool contribution may have been the result of several processes including internal waves and upwelling offshore, both of which would have introduced cooler water into the deeper portions of the shelf water mass.

<u>July 1955</u>

The thermal characteristics of the various water units and subunits in July 1955 were similar to those in June 1955, except that surface temperatures reached 68°F (Fig. 16). Many more patches of water appeared in the surface unit during this month and the base lay at an average depth of 40 feet. The surfaces were much distorted in their finer details, perhaps

by internal waves, although the changes may also have been caused by the irregular shifting of the various units in response to short period fluctuations in the current system.

Generally, the Subsurface Unit ranged in temperature from 48° to 53°, and the Surface Unit from 56° to 68°F, including the intermediate subunit with the two surface units discussed in the preceding section.

July 1956

For comparative purposes, the water unit structure for July 1956 is shown in Figure 17.

Marked differences are seen in the patterns when compared with the temperatures of the same month in the previous year. While a warm surface unit lying above a cooler subsurface unit was present in both years, the major differences existed in the subsurface layer temperatures. Where the subsurface water in July 1955 ranged from 48° to 53° over the shelf, in July 1956, the range was from 53° to 56°F. The Surface Unit is comparable to that of the previous year with a range, including the intermediate subunit, of 58° to 70°F. However, the Surface Unit was much thicker in 1956, reaching average depths of 70 to 80 feet.

Bottom water temperatures (Table II) were normally quite uniform, but changes did occur in a non-seasonal manner. An examination of bathythermograms also shows that in water deeper than 100 feet, the temperature remained essentially stable over periods of several days. A 53°F subunit was present in all seasons, and if this water represents the normal for the basic shelf water unit, then it is apparent

TABLE II

BOTTOM WATER TEMPERATURE RANGES OVER THE PERIOD
1955-56

Month	Year	Bottom Water Temperature Range °F
June	1955	49-53
July	1955	49-53
August	1955	50-53
September	1955	53-56
October	1955	53-55
November	1955	51-53
December	1955	51-53
January	1956	51-53
February	1956	51-53
March	1956	51-53
April	1956	51-53
May	1956	51-53
June	1956	51-54
July	1956	53-55
August	1956	53-55

that at some times its lower range is affected by the introduction of deeper cooler water. For example, the lower temperatures in July 1955 could represent an intrusion of slope water over the edge of the shelf.

The subsurface water in October 1955 was similar to that in July 1956, as was that representative of August 1956. On the other hand, the Subsurface Water Unit in April 1956 was more closely related to that in the summer of 1955.

August 1955

The water units and their temperatures for August 1955 are shown in Figure 18. As in the previous months, definite surface and subsurface units were defined. The Surface Water Unit was composed of an intermediate or transitional subunit, and an offshore surface subunit. The latter was under the inshore surface water in some places, and in others was apparently missing either because of mixing, or because of replacement by the inshore water unit.

In the inshore area of Redondo Canyon, the intermediate water subunit was apparently absent and the Subsurface Water Unit lay directly below the offshore surface subunit. This may have been due to the exclusion of the intermediate water nearshore followed by a subsequent flow of the upper surface water directly over the deeper water in the canyon. The sharp thermocline in this area may then have been the result of shear between the surface and subsurface units.

The surface layer, including the intermediate or transitional subunit, varied in temperature from 55° to 71°F. The subsurface water varied from 51° to 54°F. The surface unit

averaged 60 to 70 feet in depth, reaching its maximum development in the central shelf area and thinning to the north and south. This was likely due to superposition of the water by current action over <u>in situ</u> water to the north and south, brought about by the deflection of the main inshore flow.

<u>October 1955</u>

The characteristic temperatures for the various water units during October 1955 are shown in Figure 19. In this month the fall season began, as indicated by the decrease in the temperature differences between the surface to the bottom, from spreads of as much as 12° in the preceding summer months. Also, the Surface Water Unit was then composed of two main units, transitional and surface, rather than three, and the nearshore warm subunit was markedly decreased and was more restricted. Surface layer temperatures, including the transitional subunit, ranged from 57° to 63°F. The subsurface water ranged from 53° to 55° and probably represented a different subsurface condition than existed earlier in the year. The boundaries of the various units are less distorted, probably because of the reduced density differences. In addition, the summer months were periods during which stronger density slopes were created in the shelf water mass, adding to the complexity of the boundaries. These were less dominant in the fall months as the vertical water temperature spread decreased.

The profile in the Point Vicente region shows that probably stronger currents were present as evidenced by the abrupt changes in boundary slopes. This area was the site of

some inversions and rapid surface temperature changes at other times of the year, so that it was likely an area of interaction between several different water units.

January 1956

The temperature characteristics of the various water subunits for the winter months is typified by those of January 1956 (Fig. 20). Surface and subsurface water temperature spreads were small, amounting to about 3°F. The transitional subunit was weak and inshore water was nearly isothermal. Diurnal heating is evidenced by small surface warm layers which became mixed into the surface layer in the afternoon by wind action.

Temperature differentials between distinct isothermal layers were small and the thermograms showed temperature gradients rather than thermoclines. Thus, water motion was more or less uniform throughout the surface unit.

April 1956

The temperature relationships between the various units for April 1956 bore marked resemblances to the generalized picture in the fall temperature structure (Fig. 21). The surface layer was beginning to develop a definite secondary structure of subunits as the main mass of the Surface Unit separated into surface warm subunits and a transitional zone. The warm inshore subunit was well developed. The thickness of the surface unit plus the transition zone averaged 100 to 110 feet which is the maximum depth of the surface layer for the year.

The Surface Unit, including the transitional subunit, ranged from 56°F to 62°F. The subsurface water ranged from 51° to 53°. The water unit differential was, therefore, about 6°, and the maximum vertical temperature spread was about 10°.

Heat Budget

An analysis of the heat budget in the bay has been made by Mr. C. G. Gunnerson, Bureau of Sanitation, Los Angeles. This appears in that Bureau's publication, "Summary Report on Oceanographic Investigations of Santa Monica Bay, July, 1956". The pertinent results of these calculations are shown in Table III.

The important facts embodied in the calculated budget are: (1) the surprisingly large potential heat contribution from existing and future man-made sources, and (2) the important effect that such heating may have on the nearshore current system. This last is the result of the marked density slope produced at the boundaries of the sewage field as a result of its higher temperature and lower salinity as compared with the shelf water. The foam lines, slicks, films, and color changes are all visible evidence of the existence of this boundary.

The total heat contributed by the existing outfall is apparently embodied in a layer of slightly diluted sea water varying in thickness from 5 to 20 feet, and covering an area of from 10 to 20 square miles. This layer has probably been formed as a result of the turbulent mixing of effluent and bottom water at the outfall terminus and subsequent mixing

TABLE III

HEAT BUDGET IN SANTA MONICA BAY

	Existing	Proposed
Hyperion		
Average flow, MGD	250	420
Ave. Temp. diff., sewage-ocean	16°F	16°F
Sensible heat to ocean, BTU/day	3.3×10^{10}	5.6×10^{10}
Heat from oxidation sewage, 50% loss, BTU/day	1.3×10^{9}	2.2×10^{9}
Heat equivalent of salinity difference, BTU/day	21.7×10^{10}	34.4×10^{10}
Redondo Steam Plant		
Installed capacity, megawatts	453	638
Assumed average output 65% installed capacity; cooling losses 3.33×10^{6} BTU/hr/mw, sensible heat to ocean BTU/day	2.4×10^{10}	3.3×10^{10}
El Segundo Steam Plant		
Installed capacity, megawatts	175	350
Using same assumptions as at Redondo, BTU/day	0.9×10^{10}	1.8×10^{10}
Scattergood Steam Plant		
Average operating capacity, mw	none	1212
Using same assumptions as at Redondo, BTU/day		9.7×10^{10}
Total sensible heat to ocean from the above installations, BTU/day	29.6×10^{10}	57.0×10^{10}
Solar Heat	Summer	Winter
Average radiation, gm-cal/cm^2/min	0.3	0.1
BTU/mi^2/day	4.4×10^{10}	1.5×10^{10}
Surface Equivalent Area		
Sensible heat		
Existing square miles	1.5	4.4
Proposed square miles	4.6	13.6
Total effective heat		
Existing square miles	6.7	19.7
Proposed square miles	13.0	38.0

with surface water and nearshore water within the sewage field. The sewage field is in steady state so that the loss of water from it by diffusion and mixing at the edges is balanced by the introduction of new effluent and of partly diluted shelf water. A warm water field covers much of the inshore portions of the bay in the summer and early fall, from the vicinity of Venice south to Redondo, and seaward as far as three miles.

It also appears, from an examination of the thermograms, that the boundary between the field and the shelf water is a rather sharp one in the winter. This is borne out by observations which indicate that the field is bounded by slicks and marked color changes. Thermally it is larger than salinity differences indicate. This implies that the recognizable thermal character of the field is maintained beyond the range of dilutions observable from salinity, or to dilutions greater than 200 to 1.

Source of Mixing Sea Water

Although evidence is limited, it is probable that the initial mixing of the discharged effluent takes place partly with the bottom water at the outfall terminus. This is indicated by the fact that the average dilution does not change appreciably during its rise to the surface, and also by the action of a subsurface current cross which moved into the boil area while a surface cross moved out with the field during brief observations in May 1956. Therefore, the initial dilutions of approximately 20 to 1 in the present discharge boil represents initial mixing of the effluent with water at the approximate depth of the pipe; the mixing water being

replenished by an inshore flow in the vicinity of the boil at depth. After the mixed water spreads over the surface, further mixing which takes place must be largely with water in the surrounding sewage field and to a lesser extent by vertical mixing with the underlying water.

Suppression of Effluent Boil Below Surface

A series of calculations using various assumed conditions of temperature and salinity have been compiled in Table IV, in order that some limiting conditions for the equilibrium positions of the rising effluent may be considered. The computations are based on various dilutions in the proposed boil, an assumed depth of discharge of 200 feet, a normal shelf water salinity of 33.50 o/oo, a mixed water temperature of 50^{o} to 55^{o}F in the rising column for each chosen dilution, and various surface temperatures typical of each season of the year in the approximate area of the proposed outfall. It is also assumed that fresh sea water will be continually available at the end of the outfall, so that no appreciable change in the salinity or temperature of the rising column will occur after initial dilution. It is evident that, as a whole, the above criteria are the optimum conditions. It is probable that the temperature of the rising effluent will be close to those assumed, but its salinity may be higher. It is also probable that the approach of new shelf water will not be fast enough to prevent the mixing of previously diluted sea water with the effluent, causing a lighter mass than is here assumed. In any event, the calculations indicate times at which suppression may possibly be expected.

TABLE IV

CALCULATED DENSITIES OF VARIOUS MIXED WATER COLUMNS

COMPARED TO SEVERAL SURFACE WATER DENSITY CONDITIONS

Mixed Water (Assuming effluent chlorinity of 0.25°/oo)

Dilution	20:1	50:1	100:1	200:1
50°F	1.02459	1.02530	1.02556	1.02569
55°F	1.02409	1.02480	1.02505	1.02518

Shelf Surface Water Unit

Temperature	55°F	58°F	61°F	64°F	66°F
Density	1.02529	1.02497	1.02459	1.02419	1.02392

Maximum Temperatures for Suppressing Effluent-sea water Mixture

Dilution	20:1	50:1	100:1	200:1
Mixed water at 50°F, Surface T less than-	61°F	55°F	52°F	50°F
Mixed water at 55°F, Surface T less than-	65°F	58°F	56°F	55°F

It is evident from the tabulated data that the higher the dilution at the diffuser, the greater the possibility that the field will tend to attain a subsurface level of equilibrium. Also, the warmer the mixed effluent-shelf water, the more likely the tendency for the column to penetrate through to the surface. The best conditions for suppression should occur during the summer and this is the season for which such an event would be most welcome from a publicity and health point of view. However, the differential in all cases is a delicate one. It is quite certain that the column will tend to rise above its level of equilibrium initially due to is momentum. Thus, a large differential in density must be present to insure the subsurface spread of the mixed water. The critical factors would appear to be the dilution achieved in the diffusers and the temperature of the mixed water.

THE AREAL DISTRIBUTION OF WATER TEMPERATURE AND RELATED WATER MOTION

Introduction

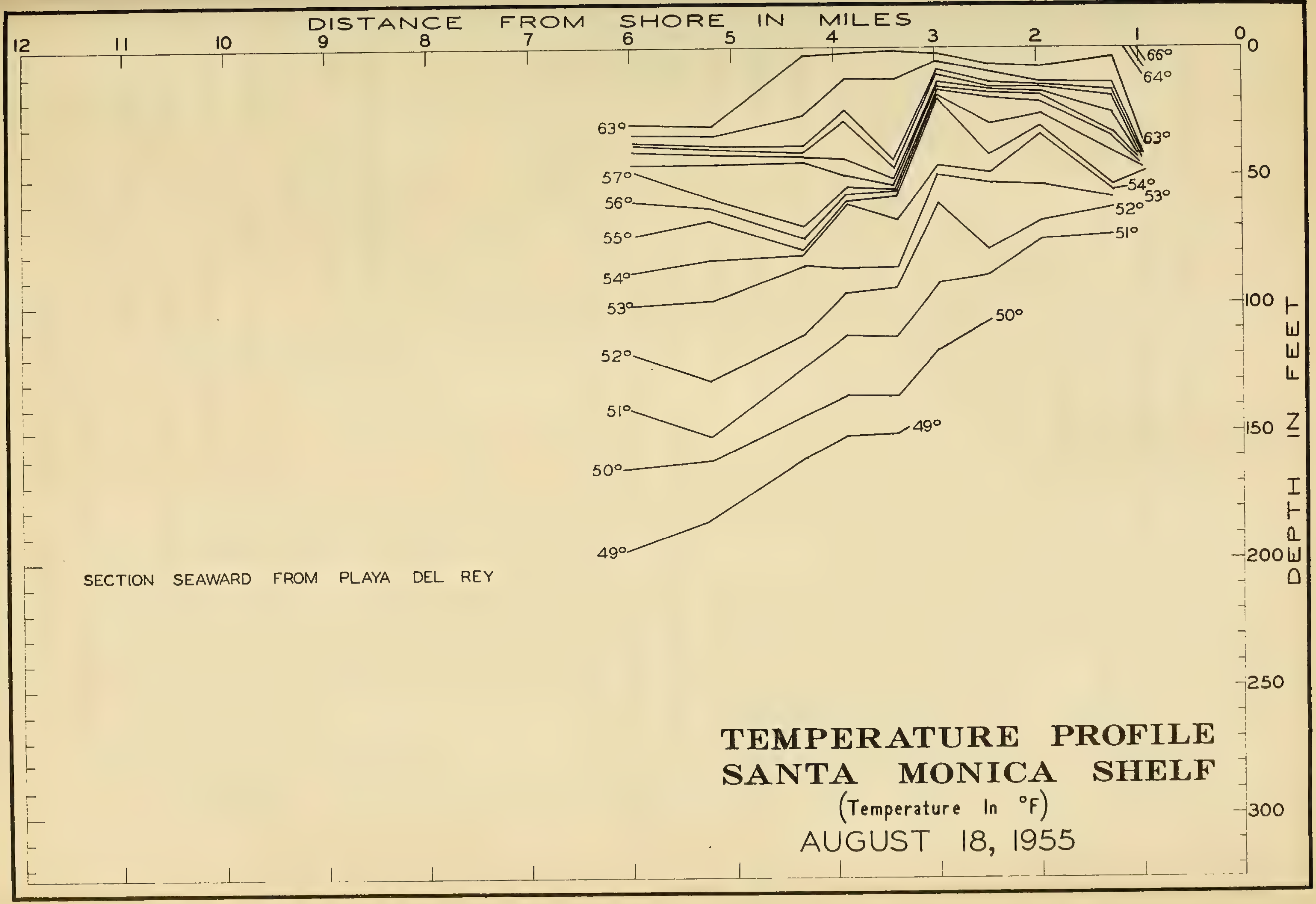
The areal distribution of temperature in coastal waters is of interest in many phases of the marine sciences, but in this study its main value is in the interpretation of water motion in Santa Monica Bay. The flow of ocean currents in the bay and the distribution of the various water units derive their importance from the necessity of determining with some degree of accuracy the motion of the proposed sewage field. Because of this importance and the fact that any decision as

whether or not the proposed outfall should be constructed must be based on the current patterns, empirical methods for the measurement of direction and velocity were employed. Neither current meters nor drogues give more than an instantaneous trace of the water motion in a restricted locality, and drift cards represent merely the upper mixed layer and its net motion. Furthermore, the distribution of surface and sub-surface water units and their impression on the water structure of the bay as a whole can in only a casual way be interpreted by these methods of measurement.

On the other hand, there is no theoretical or mathematical method by which density patterns can be used to compute current flow in shallow water overlying continental shelves. Determinations of ocean currents from the slopes of isobaric surfaces assume level surfaces at some depth along which no horizontal component of gravity is active. Such level surfaces are usually taken at depths of 500 meters or more. Thus, the preparation of dynamic height anomalies and the subsequent construction of the geopotential topography of isobaric surfaces by conventional methods is not possible in shallow water.

However, it is believed that density currents can exist in shelf water and the basic problem becomes one of determining, at least in a qualitative way, their directions if not their velocities. It is only logical to assume that the larger scale differences in temperature in Santa Monica Bay are related to the character of circulation. A temperature profile, such as that obtained on August 18, 1955 (Fig. 22), is an example of

Figure 22. Vertical temperature profile, seaward from Playa del Rey, August 18, 1955.



TEMPERATURE PROFILE SANTA MONICA SHELF

(Temperature In °F)

AUGUST 18, 1955

temperature gradients that might be associated with currents in the bay. The initial assumption which can be made is that the density of water near the surface of the sea generally is more dependent upon the temperature than upon the salinity. Since vertical profiles show that the salinities in these coastal waters are nearly constant with depth and with distance from shore, examination of temperature conditions alone may permit first approximations as to the directions of the currents. Under such a theme of utilization, the term "lighter", as used with density slopes, may be replaced by "warmer", and "denser" by "colder". Bearing these conditions in mind and for an understanding of the following discussion, one has then the simple rule: _In the northern hemishpere the warmer water lies on the right hand side of an observer looking in the direction of the current, and the colder water lies on the left hand_.

The Effect of a Temperature Gradient

A change in water temperature per unit distance is called a _temperature gradient_. The term may be used to describe a change in temperature with depth (vertical temperature gradient), or it may refer to a change per unit distance along a level surface (horizontal gradient). The following discussion deals entirely with horizontal temperature gradients which are most conveniently represented by charts showing the topography of selected isothermal surfaces.

The gradients associated with slopes of isothermal surfaces are directly related to currents only under four

conditions: (1) the water is uniformly stratified with respect to salinity, (2) the horizontal temperature gradient becomes zero at the bottom, (3) the topography of an isothermal layer is not distorted by other factors, and (4) the effect of friction is negligible. The first condition is approximately fulfilled in Santa Monica Bay. The second is not, for from the great number of temperature measurements taken over the San Pedro and Santa Monica shelves, it is quite apparent that no such level surfaces exist in these waters. The third condition also is not fulfilled, although its relative importance is difficult to assess, as is the effect of friction.

In spite of these limitations, it can be demonstrated that there is a general correspondence between the current directions as deduced from temperature distribution and those obtained from empirical measurements.

The paths of the surface and subsurface drogues used in May, June, and July 1956, and the corresponding temperature surfaces are shown in Figures 23, 24, 25, 26, and 27. The paths of the drogues in the surface layers followed closely the thermal gradients. However, the subsurface drogues were not as closely aligned with the isothermal lines as one might have suspected. It is believed that three possible uncontrollable situations may have resulted in the non-conformity. First, since the contours were drawn free-hand with no attempt to correct the bathythermograph traces, a slight variation or correction could easily superimpose the contours and the drogue path. Second, the positions of the bathythermograph casts were taken while the ship was underway, so that a

Figure 23. Depth to 55°F isotherm and drogue track, May 4, 1956.

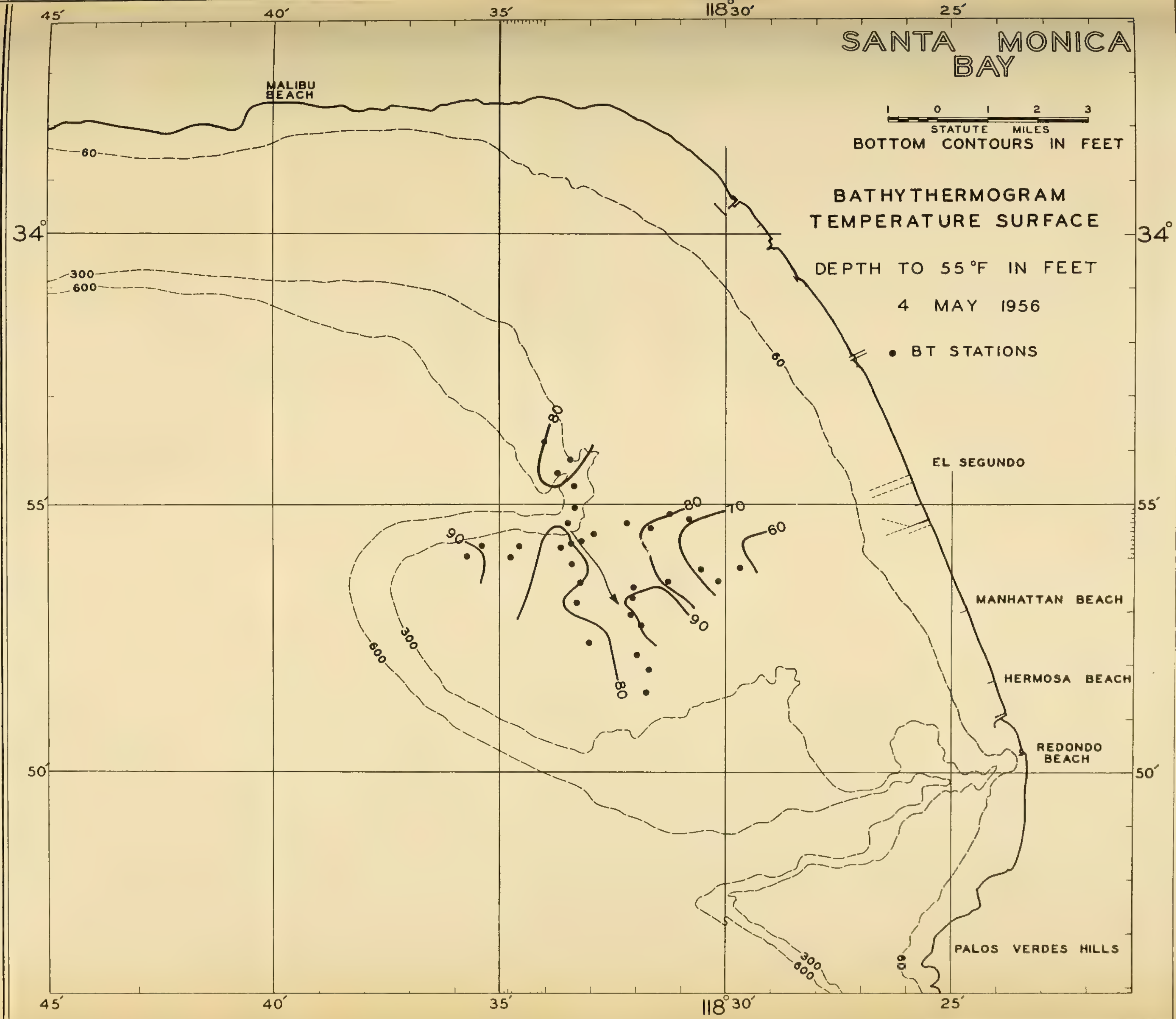

SANTA MONICA BAY
STATUTE MILES
BOTTOM CONTOURS IN FEET
BATHYTHERMOGRAM TEMPERATURE SURFACE
DEPTH TO 55 °F IN FEET
4 MAY 1956
• BT STATIONS
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS

Figure 24. Depth to 56°F isotherm and track of deep drogue, May 4, 1956.

Figure 25. Depth to 66°F isotherm and drogue track, June 28, 1956

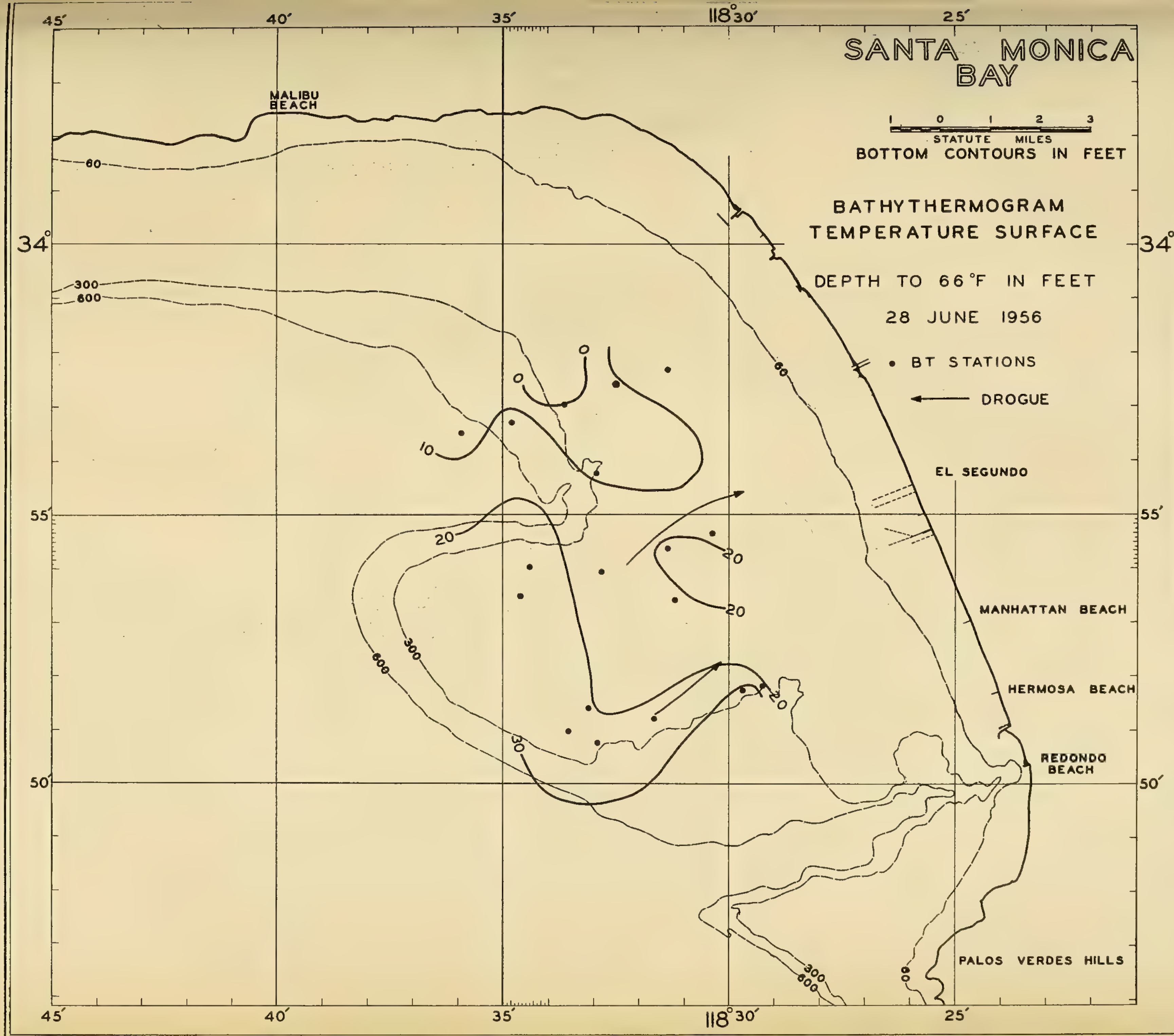

SANTA MONICA BAY
STATUTE MILES
1 0 1 2 3
BOTTOM CONTOURS IN FEET
BATHYTHERMOGRAM TEMPERATURE SURFACE
DEPTH TO 66°F IN FEET
28 JUNE 1956
• BT STATIONS
DROGUE
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
45′
40′
35′
118°30′
25′
34°
55′
50′
60
300
600
0
10
20
30

Figure 26. Depth to 65°F isotherm and drogue track, August 10, 1956

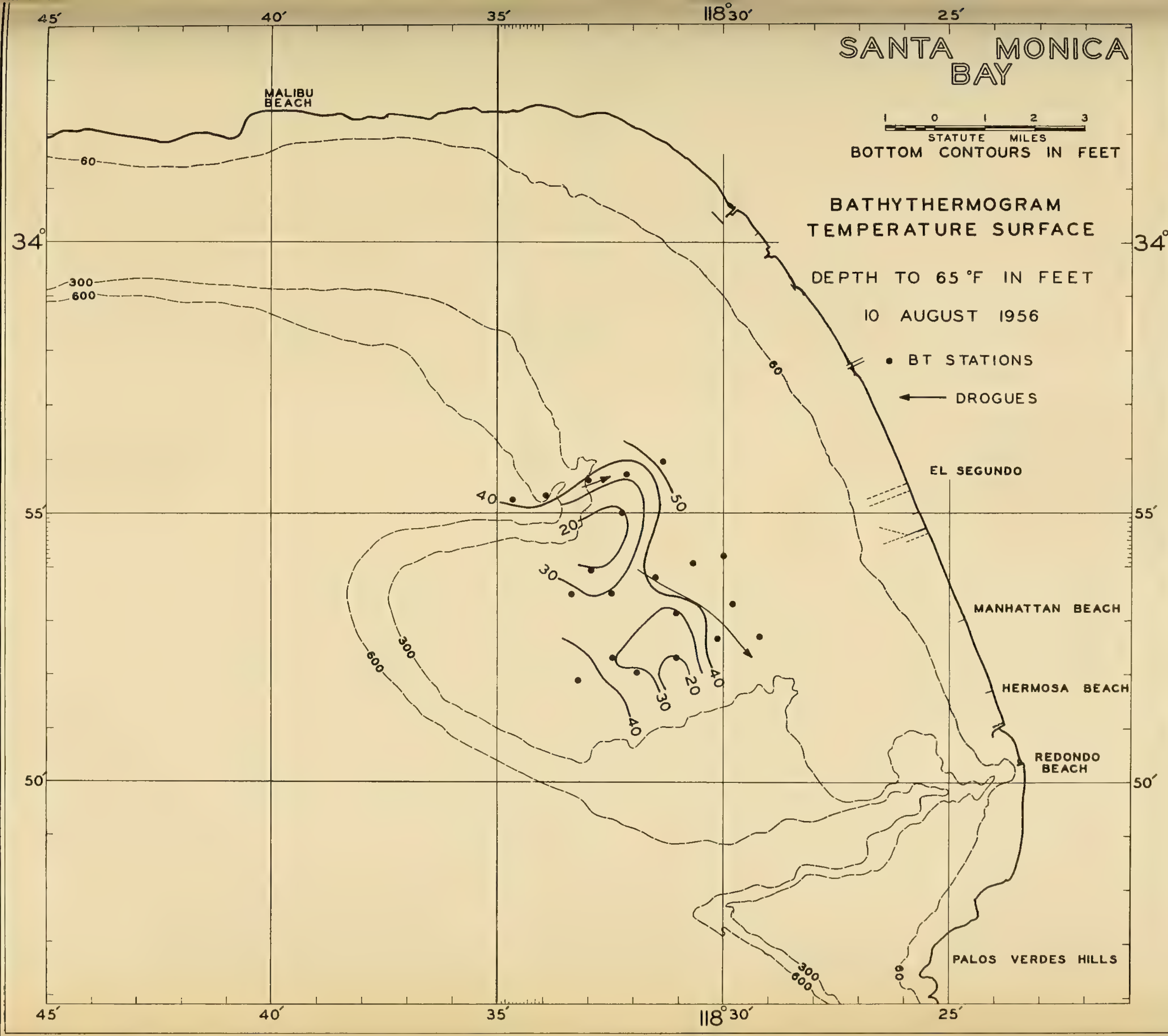
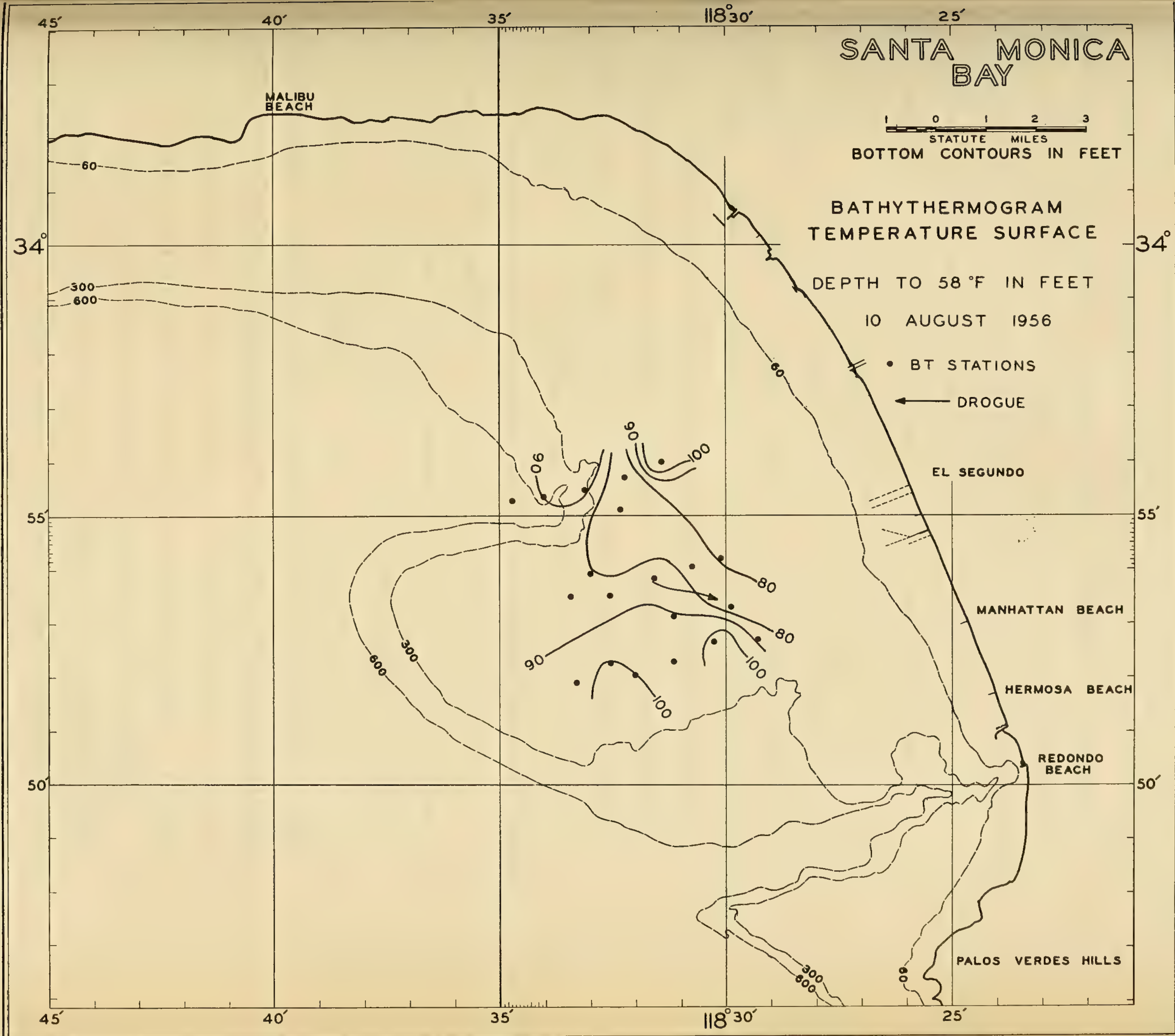

SANTA MONICA BAY
STATUTE MILES
1 0 1 2 3
BOTTOM CONTOURS IN FEET
BATHYTHERMOGRAM
TEMPERATURE SURFACE
DEPTH TO 65 °F IN FEET
10 AUGUST 1956
• BT STATIONS
DROGUES
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
45′
40′
35′
118°30′
25′
34°
55′
50′
60
300
600
20
30
40
50

Figure 27. Depth to 58°F isotherm and drogue track, August 10, 1956


SANTA MONICA BAY
STATUTE MILES
1 0 1 2 3
BOTTOM CONTOURS IN FEET
BATHYTHERMOGRAM TEMPERATURE SURFACE
DEPTH TO 58 °F IN FEET
10 AUGUST 1956
BT STATIONS
DROGUE
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
45′
40′
35′
118°30′
25′
34°
55′
50′
60
300
600
80
90
100

slight error in navigation could displace the contoured surface the 500 or 600 feet necessary to bring the isothermal lines into agreement. Third, the surface float used for identification of the subsurface drogue cross was a 12"x12"x24" block of wood which presented a large surface area. The movement of the upper water layer may have been such that the track of the subsurface drogue was not the one it might have followed had it been able to move freely. Even with these possible sources of error, there is a remarkable correlation between the drogue paths and the associated thermal gradients.

It is because of this correlation that the effects of temperature gradients are discussed below and that certain conclusions regarding the circulation in Santa Monica Bay are drawn from temperature distribution.

Assuming now that water motion is related to a horizontal temperature gradient, the rate of movement of the water increases as the gradient becomes larger. If the gradient were to act alone, the water would flow in the direction of the gradient. Movement of water in the ocean, however, is profoundly modified by an effect due to the rotation of the earth (Coriolis force) and the result is a flow perpendicular to the gradient, that is, parallel to the isotherms. This is the reason, therefore, for the statement made above, for we find that as a particle of water begins to flow down the gradient, it is deflected to the right in the northern hemisphere so that the net result is a flow along isothermal lines rather than across them. This deflecting reaction (force) is a function of the sine of the latitude, acts at right angles

to the horizontal motion of the water, and is directly proportional to the horizontal velocity.

The current velocity is inversely proportional to Coriolis force, but in qualitatively comparing the velocities associated with varying slopes of isothermal surfaces within a restricted range in latitude (Santa Monica Bay), Coriolis force can be considered as contant and the relative velocities are therefore directly proportional to the slopes.

Centrifugal and deflective forces always act perpendicular to the instantaneous direction of a wind in the atmosphere and the same is true of water motion in the sea. It can be shown, mathematically, that when the three forces (gradient, centrifugal, and deflective), are in balance, a steady state is reached. The resultant wind (or current, in the case of water) is called a gradient wind. Such a gradient flow occurs after the gradient has initiated the movement, although the gradient itself may be formed by a current driven by some external force (the wind, for example). If a gradient current is present which flows along isolines that are parallel and straight, it is called a _geostrophic current_. Currents of this nature are know to exist in the open sea, and undoubtedly they also occur in shelf waters. However, in the shelf area, where many conditions tend to disrupt water motion, it is unlikely that a "steady state" of more than a few hours duration ever occurs.

Some Conditions Causing Density Currents

Wind. In the open ocean the stress that the wind exerts on the sea surface leads directly to the development of a shallow wind drift, and the transport of water by the wind

drift leads to an altered distribution of density and the development of corresponding currents. In the northern hemisphere, the wind drift at the surface is directed 45° to the right of the wind and with increasing depth, the angle between the wind and the current increases while the velocity decreases. If the current at equal depths is represented by an arrow of the correct direction and a length corresponding to the velocity, these arrows will form a spiral "staircase", the steps of which become shorter as the depth increases. Thus, a depth can theoretically be found at which the current flows in a direction opposite to that of the surface current. However, at that depth the velocity approaches zero. Such a theoretical condition can only develop, however, in the open ocean in regions where the wind blows with a constant velocity and direction over wide areas. No such simple application can be used in shallow coastal waters where wind velocities and directions change continuously throughout the day and where there are countless modifying features caused by the shoreline, shoal water, tidal effects, and unequal heating in the nearshore zone.

Near coasts the secondary effect of the wind becomes important and dominant. A wind blowing parallel to the coast, with the land on the right hand side looking downwind, leads to the transport of light and warm surface water toward the coast. The coast acts as a barrier so that the light and warmer water piles up against it, and at some distance denser and colder subsurface water must rise to replace that carried to the coast. The distribution of density is altered and a current develops

that flows in the direction of the wind, according to the rule that the lighter water shall be on the right-hand side of the current. Warm water placed adjacent to the coast by other means, such as that developed by the outfalls in Santa Monica Bay, also results in currents of this nature.

Now consider a wind with the coastline on the left of the direction of travel. Light and warm water is necessarily transported away from the coast and is replaced by denser and colder subsurface water. This process, which is know as upwelling, also leads to an altered distribution of density to which a current flowing in the direction of the wind corresponds.

Each of these wind effects occurs in Santa Monica Bay and is instrumental in developing water motion which can be readily identified by horizontal temperature patterns. In many instances, it can be shown that the flows along isotherms are directly related to wind directions, but modifications occur which are not so easily interpreted. Other factors, therefore, must be effective in modifying the density flows.

Tidal Currents. Tidal currents do not bring about the transport of water over large distances. They vary from one locality to another, depending upon the character of the tide, the depth to the bottom, and the configuration of the coast, but in any given locality they repeat themselves as regularly as the tides to which they are related. The most important aspect of the tidal currents in coastal areas is that they contribute greatly toward the stirring of water layers. Because of their minor effect on net water motion, they frequently are obscured by the forces of density slopes.

Internal Waves. Internal waves that may develop currents are generally of tidal period. In an internal wave, one or more density surfaces at intermediate depths remain level, however, and the slopes that result above or below a level surface are in opposite directions. The corresponding currents are in opposite directions and if internal waves of different periods are present simultaneously, a complicated pattern of currents results. This is especially true in shelf waters where shoaling conditions may cause the breaking and re-development of a multitude of internal waves with several differing periods. It is recognized that temperature patterns in Santa Monica Bay may be frequently complicated by this feature of the subsurface water motion.

The Temperature Distribution and Currents

Steady State Conditions

Along the Malibu coast and in the southern part of the bay adjacent to the Palos Verdes Hills, cool water units are nearly always present. The temperature differential between the water nearshore at Malibu and that offshore is generally not great and the occurrence here of this water pattern is attributed to upwelling. At the present state of knowledge concerning the existence of cooler water nearshore, it is impossible to determine whether the occurrence along Malibu represents an upward displacement of subsurface water, or a continuously rising flow associated with upwelling or divergence. Either is possible, but because of the wind patterns in the area, it is more likely that an intermittent upward

flow occurs. Whatever the action, the mechanism is unimportant to this discussion.

The cold water unit in the southern part of the bay is usually most intense along the western shore of the Palos Verdes Hills. Frequently its extent is minor and the temperature differential between it and adjacent water units is great. At such times it is close to shore with a steep thermal gradient separating it from the offshore water. At other times, the unit spreads into the bay and along the coast as far north as Redondo. Both temperature differentials and gradients are small during such an expansion.

The existence of these cold water units almost continuously throughout the year establishes thermal conditions which do not occur in any other parts of the bay. The occurrence along the Malibu coast is easily explained by the dominant westerly winds with resultant upwelling action. That along the Palos Verdes shore is not likely due to wind action because the orientation of the coast to the winds is such that surface water should be directed toward the shore rather than away.

There appear to be two possible explanations for this cooler water. It is known that unusually rugged topography on the sea floor in shallow water areas can result in the projection of subsurface water to the surface (Stevenson and Gorsline, in press). The region of cold water in this part of the bay fluctuates across Redondo Canyon, the shelf projection south of the canyon, and the narrow shelf adjacent to the Palos Verdes Hills. It is not unreasonable to assume, therefore, that tidal currents and internal waves flowing over

these extreme variations on the sea floor could cause the surface projection of cooler water. On the other hand, it might be unreasonable to assume steady state conditions, for certainly variations in the periods of tides and internal waves would be sufficient to cause marked differences in the occurrence of the water unit. Such variations may be why the varying intensities as noted do occur.

Another contributing agency to the cold water area may be from the more or less constant flow of water out of the bay to the south. Flushing of the shelf water occurs normally by this current, which is established by water conditions within the bay rather than by those that may exist along the southern border. A constantly moving current here would of necessity require the existence of cooler water on the left of its course, i.e., adjacent to the shore. Because the current originates in the bay, as an overflow condition, for example, the temperature slopes noted would be developed as a consequence of the flow. Thus, varying conditions within the bay, causing varying current flows to the south, would result in considerable variation in the cold water unit.

Annual Variations

Surface Water. There is a seasonal cycle in the distribution of water units, but it is more indicative of two rather than four seasons. The major distinction between the two seasons is the location of cold water units with respect to the Santa Monica-Redondo coast. In the colder months of the year, November through May, the water three miles or more from shore is warmer than that inshore. The reverse is true in the

warmer months, June through October. Exceptions to this general distribution do occur, as in March when the water was cooler offshore, and in June when it was cool nearshore. These differences can be ascribed to particular weather conditions that existed at the time of the temperature survey. Obviously, digressions from the general patterns may have occurred during other times of the year, but were not sampled during this survey. These differences that occur from time to time throughout the year indicate the close relationship between the water distribution and the immediate meteorologic conditions, in addition to the annual cycle. Nevertheless, the biannual patterns are too regular to dismiss lightly and it is certain that the two-season distribution is real.

The location of the major portion of warm and cold water determines the basic direction of water motion that is consequently established. This is especially true within three miles of shore where temperature slopes are better developed than farther offshore. Thus, a general southerly flow exists in the winter and a northerly flow in the summer. The temperatures from the data taken in April, May, and September indicate no north or south component, and such periods could well have occurred in other months. However, during most of the year a water motion parallel to the eastern shore of the bay is present and material carried shoreward must necessarily follow a devious path, either to the north or south.

In all months there are parts of the bay where no isothermal slopes are developed. There is no apparent regular distribution of these flat thermal surfaces, except that they

occur offshore more frequently than inshore. There were no instances when the entire Surface Water Unit was "flat" throughout the whole bay. Every month showed temperature slopes of sufficient magnitude to be associated with water motion somewhere. In areas where the surface layer exhibits no gradients, the wind is the dominant force contributing to water motion. Since these surfaces occur almost exclusively seaward of a line about three miles from shore, and since the winds here are almost prevailing westerlies, the surface drift must be toward shore with a slight southerly component. The angle between the wind direction and the water motion will not be as great as is known to occur in the open ocean, but from experience is closer to 20°. Therefore, an average condition in any given month would allow surface water in the outer portion of the bay to move shoreward to the southwest until it reached a point two to three miles from the coast where it would be carried either to the north or to the south prior to reaching the beach.

It is of interest to note that when flat surfaces exist nearshore, there are always gradients offshore which rarely indicate an easterly flow. Thus, even though drift may be to the east inshore, the initial travel from the offshore area will be north or south. Only a rare coincidence of water temperature conditions result in a continuous flow to the east of water originating farther than three miles from the coast.

Subsurface Water. The Subsurface Water Units do not show the biannual distribution to the same degree as the surface layers. Except for two months, June and October, colder water

lay next to the shore with sufficiently strong temperature slopes to establish a southerly drift. However, during the summer period, there were two months during which cold water was nearshore in part of the bay and offshore along the rest of the coastline. Thus, during the months when the surface layers next to shore were consistently warm, the Subsurface Water Unit did show marked variations from its constant pattern in the other months.

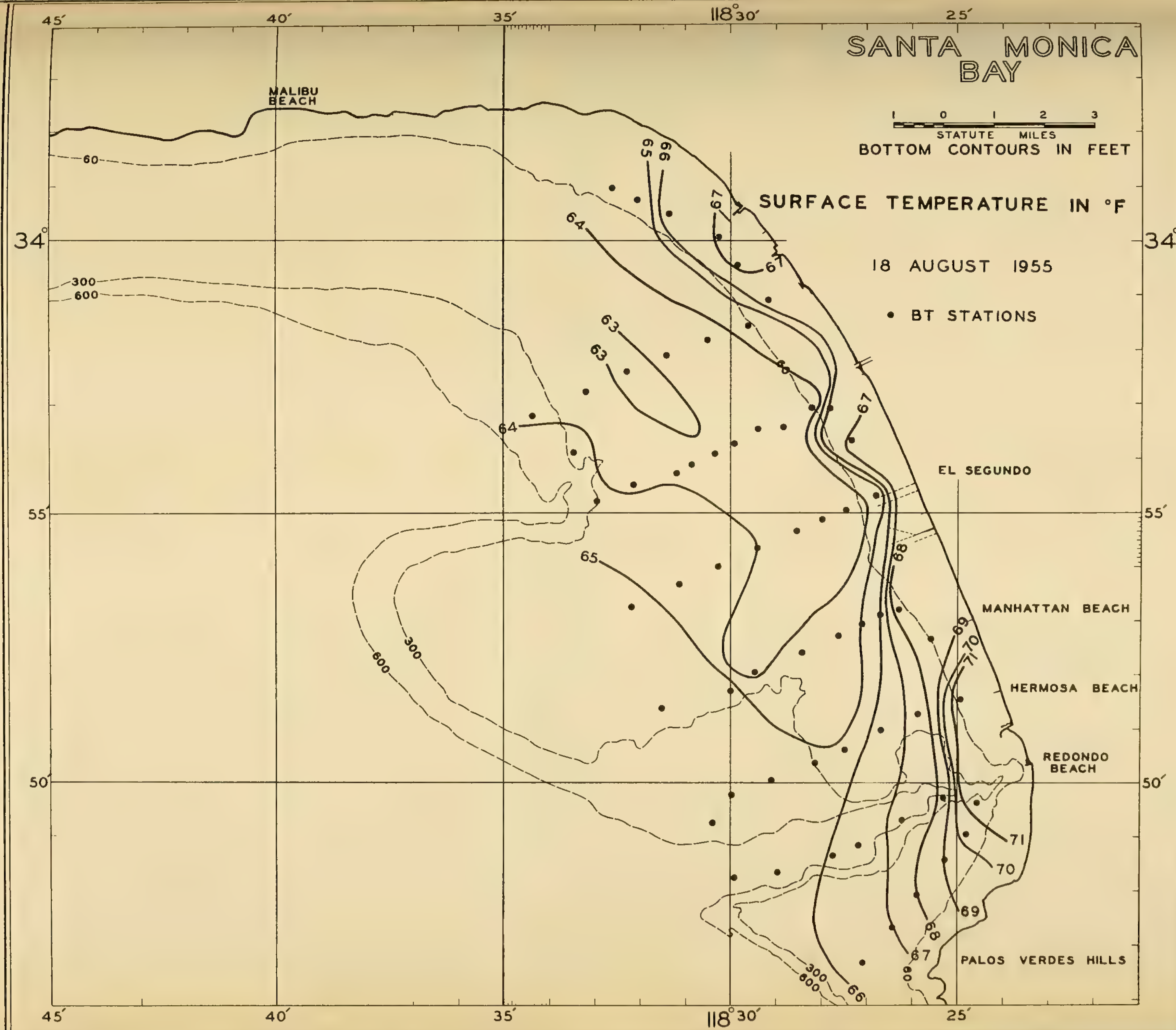
The flat surfaces which occurred in the upper water in the offshore area were not present in the lower layers. Only in October were the thermal surfaces of the entire outer shelf flat, although in all but two of the remaining months there were low gradients in portions of the offshore area. The inshore subsurface unit had flat topography over the entire bay during three months, February, May, and September, and no slopes in portions of the area in seven of the remaining nine months. Taken as a whole, therefore, the Subsurface Water Unit is more complex throughout the year than the surface layer, but the annual cycle is less extreme.

Meteorologic Relationship of the Annual Distribution. The shift in the major cold and warm water units is probably associated with the oscillation of the dominant winds along the southern California coast. A dominant, but not prevailing, northwest wind blows during the winter and even though it may be frequently modified by frontal winds, its constancy over the ocean is remarkable. The Santa Monica Mountains diminish the force of these winds along the Malibu shore, but this effect does not extend beyond the city of Santa Monica. South to about

Redondo, therefore, the northwest wind causes the surface water to be driven offshore resulting in mild upwelling along the coast. The upwelling action is intense because of the broad shelf opposite the shore, so the thermal gradient is usually gentle, the surface water nearshore rising from only about 20 or 30 feet. Thus, the seaward flow, when it occurs, is not strong and does not cancel water motion to the east, although certainly it must reduce its velocity to some extent. Under some wind conditions the surface water is driven from the bay along the western shores of the Palos Verdes Hills. More commonly, though, it is caught between Redondo and Palos Verdes Point until a wind shift or a varying current condition causes it to be redistributed.

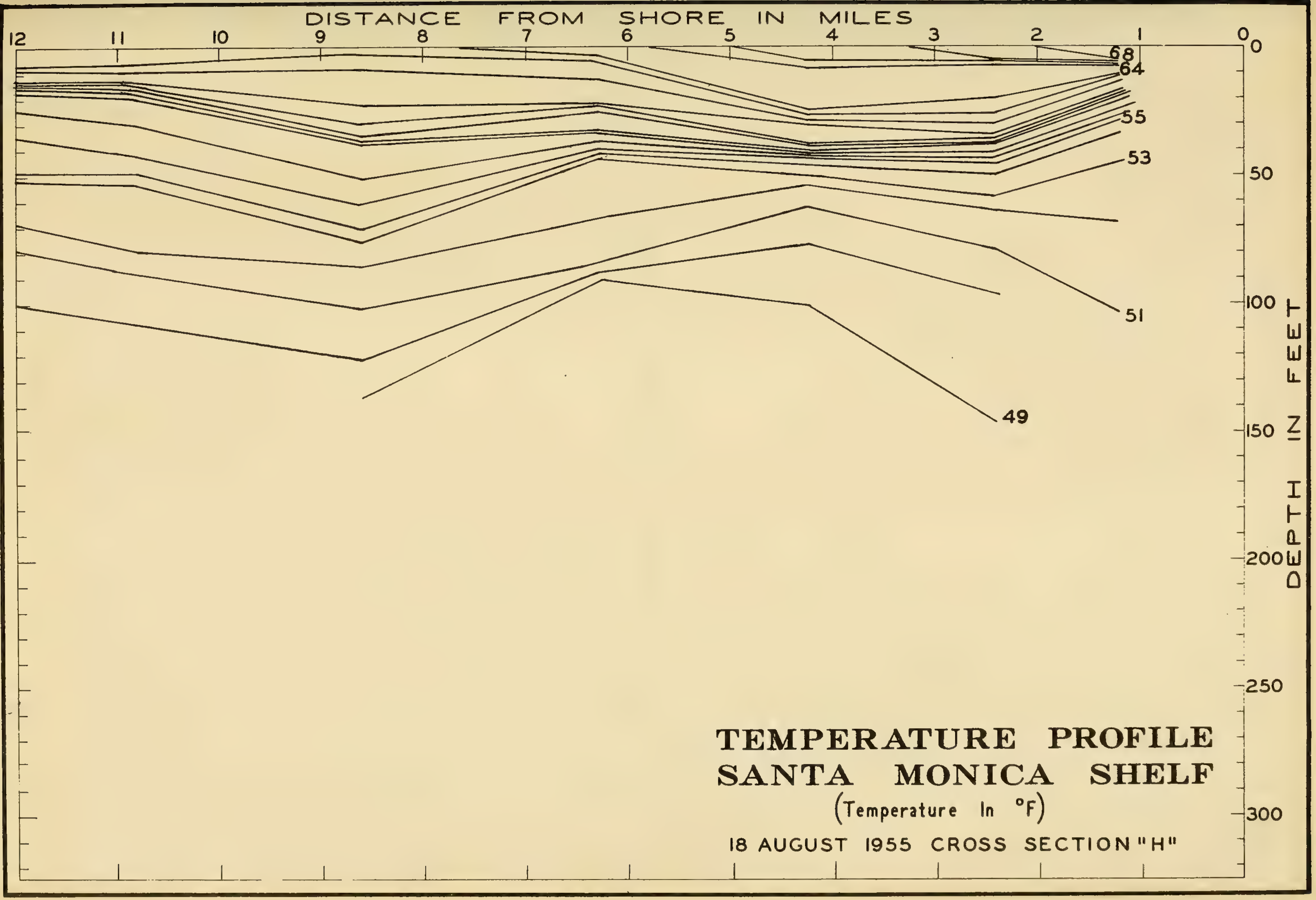
In the late spring the dominant wind pattern along the southern California coast shifts to the west and southwest. The resulting surface water flow causes warmer and lighter water to pile up along the bay shoreline, particularly in the southern part near Redondo (Figs. 28 and 29). The temperature of the water is further increased by heating in the shallow nearshore zone and the addition of heat from man-made sources (Fig. 30). This deepens the warm surface unit and causes an expansion seaward resulting in a gradient current flowing to the north. Many variations in the size, temperature, location, and intensity of the nearshore warm water obviously result from the varying winds and the magnitude of solar insolation. Even so, the consistency of this summer characteristic is readily apparent.

Figure 28. Surface temperatures, August 18, 1955.



SANTA MONICA BAY
STATUTE MILES
BOTTOM CONTOURS IN FEET
SURFACE TEMPERATURE IN °F
18 AUGUST 1955
BT STATIONS
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS

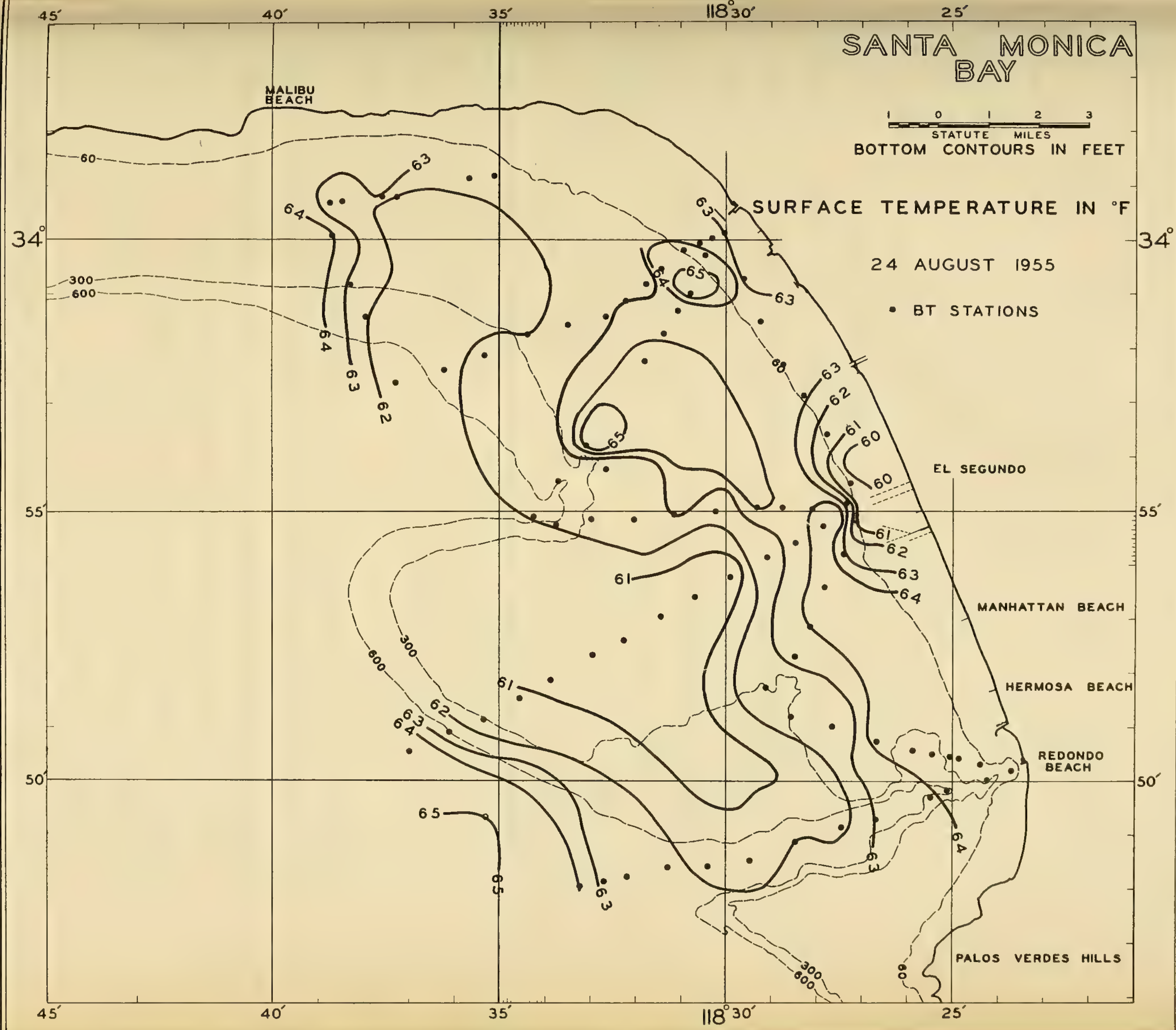
Figure 29. Vertical temperature profile in a north-south direction extending from Palos Verdes Point, August 18, 1955.



TEMPERATURE PROFILE
SANTA MONICA SHELF
(Temperature In °F)

18 AUGUST 1955 CROSS SECTION "H"

Figure 30. Surface temperatures, August24, 1955.

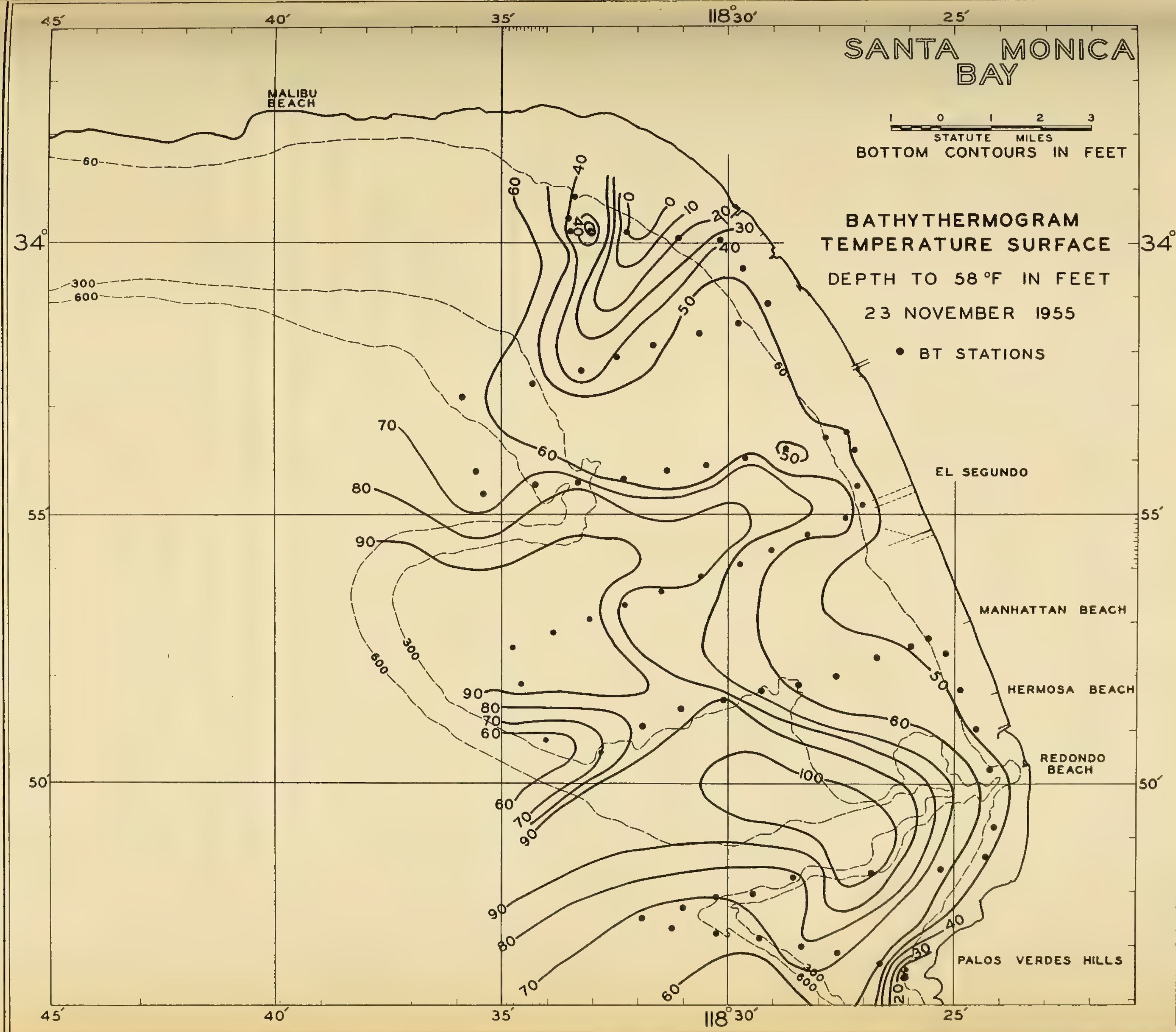

SANTA MONICA BAY
STATUTE MILES
BOTTOM CONTOURS IN FEET
SURFACE TEMPERATURE IN °F
24 AUGUST 1955
• BT STATIONS
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
34°
55′
50′
45′
40′
35′
118°30′
25′

Seasonal Distribution

Winter. The winter season, i.e., those months when cold water is characteristic of the nearshore area, begins in November and ends in May. Within three miles of the Santa Monica-Redondo shoreline the gradient current is toward the south, although its velocity and direction along any part of the coast varies considerably. The nearshore area, where the least motion results from thermal gradients, is in the central part of the bay between Playa del Rey and Manhattan Beach. Here flat isothermal surfaces are common and when thermal slopes occur, they are gentle. Thus, currents due to winds and tides are more effective and the semi-diurnal tidal oscillations are frequently the dominant motion in a north and south direction. There are also conditions when the extent of the upwelling along the Malibu shore may be so great that a cold tongue of water projects to the south causing an easterly flowing current opposite the Santa Monica-Venice shoreline.

The spatial distribution of the Surface Unit on November 23, 1955 exemplifies many of the conditions characteristic of this season (Fig. 31). The 58°F temperature surface intersects sea level nearshore north of Malibu and is within 15 feet of the sea surface off Palos Verdes. Offshore it deepens to a maximum depth of 96 feet over the edge of the shelf. Any currents generated by the isothermal slopes must be toward shore off Santa Monica, Playa del Rey, and Redondo, and south out of the bay opposite the Palos Verdes Hills. Southerly drift is likely negligible or non-existent due to the gently

Figure 31. Depth to the $58^{\circ}F$ isotherm, November 23, 1955.



SANTA MONICA BAY
STATUTE MILES
BOTTOM CONTOURS IN FEET
BATHYTHERMOGRAM TEMPERATURE SURFACE
DEPTH TO 58°F IN FEET
23 NOVEMBER 1955
BT STATIONS
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
34°
55'
50'
45'
40'
35'
118°30'
25'

sloping gradient to the east. Thus, net motion in the upper surface layers opposite Venice and Manhattan Beach would be strictly due to wind drift.

The topography of the subsurface water unit was similar to the upper layer in November with temperature slopes oriented so as to develop landward flows off Santa Monica and Manhattan Beach, and a southerly flow out of the bay opposite Redondo (Fig. 32). A gyral of cold water was prominent about four miles offshore from Playa del Rey and a gyral of warm water elongated parallel to the shore occurred over the shelf south of Redondo Canyon. The northern gyral may have aided in producing a seaward flow of water opposite Hyperion, but the gradient is gentle and in that area the currents were probably the result of minor fluctuations with tidal periods.

The least complex pattern noted during the winter period occurred on May 23-24, 1956 (Fig. 33). That this pattern was drawn from temperatures taken at night in the absence of wind and solar heating may indicate a rather rapid change in the conditions of the mixed layer from the more complex slope systems developed in the daytime. There was no horizontal gradient over the entire inshore area on those days and the only semblance of slopes occurred offshore and off the Palos Verdes Hills; both trending in a southerly direction. Water motion in the upper layers under such conditons is controlled by tides and winds (Fig. 34).

As with the surface unit topography, the subsurface water had a relatively simple temperature distribution. There was a general rise of the isotherms toward shore, but for the most

Figure 32. Depth to the $55^{\circ}F$ isotherm, November 23, 1955.

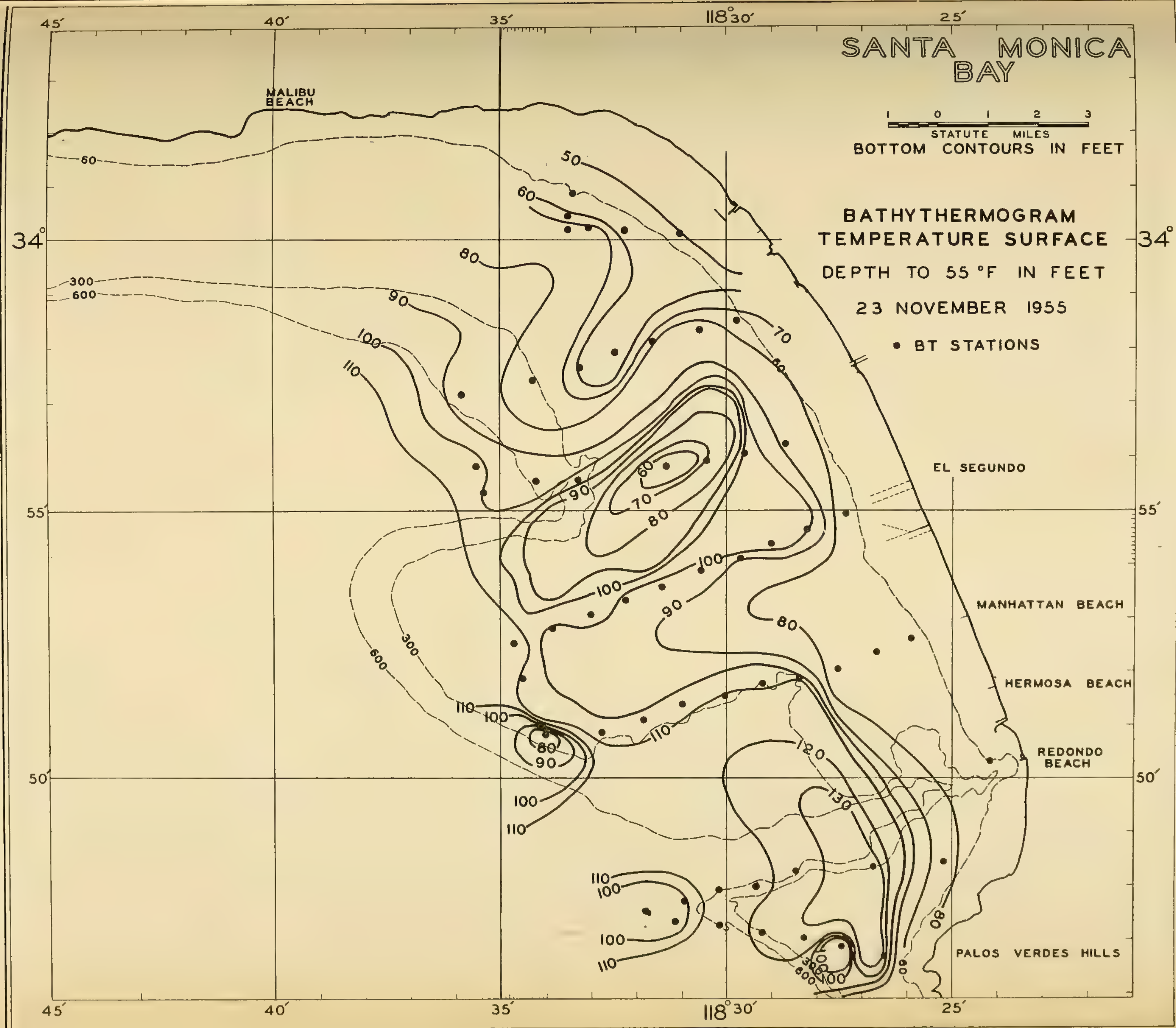

SANTA MONICA BAY
STATUTE MILES
BOTTOM CONTOURS IN FEET
BATHYTHERMOGRAM TEMPERATURE SURFACE
DEPTH TO 55 °F IN FEET
23 NOVEMBER 1955
• BT STATIONS
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
118°30′
34°
55′
50′
45′
40′
35′
25′

Figure 33. Depth to the $60^{\circ}F$ isotherm, May 23-24, 1956.

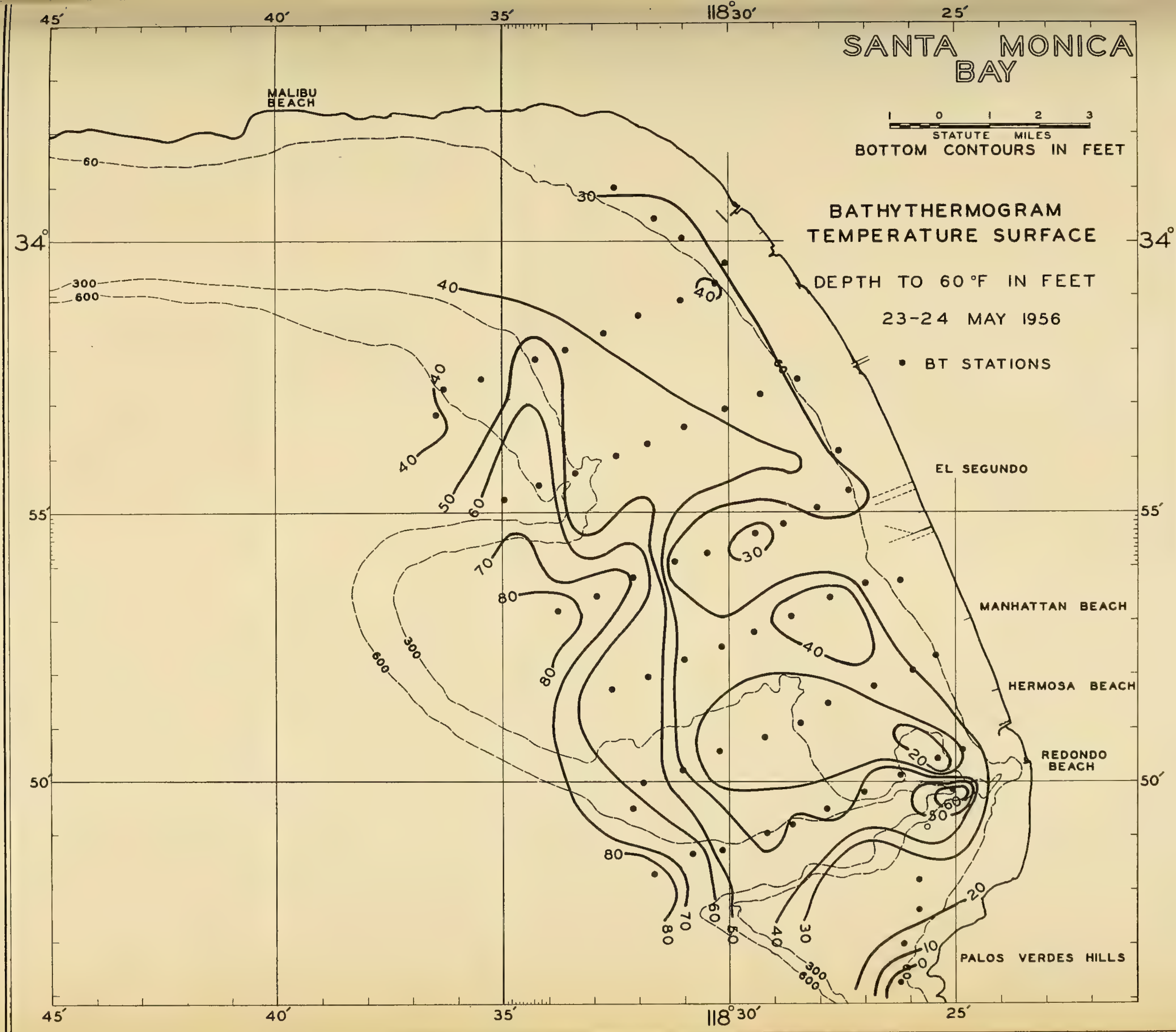
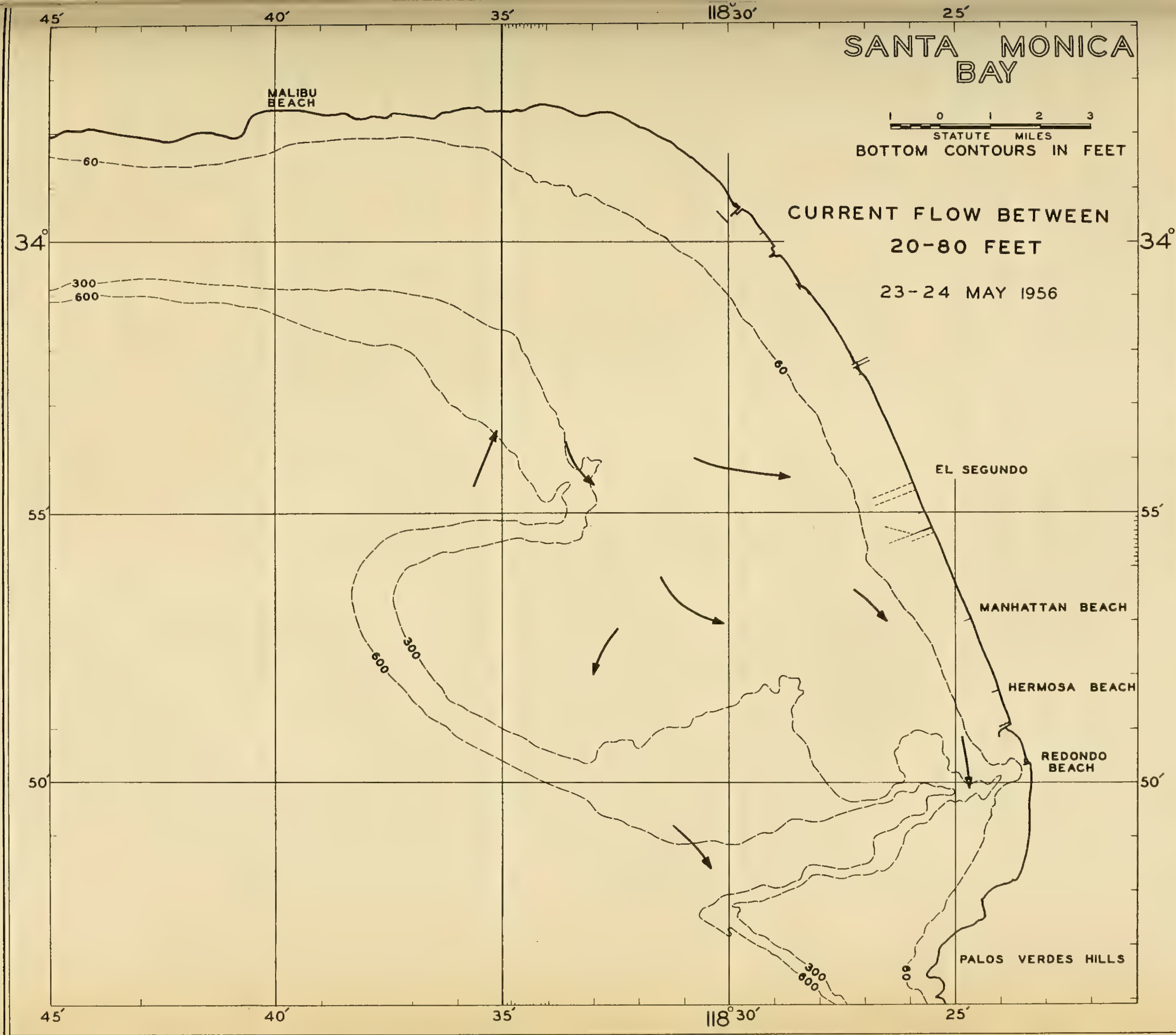

SANTA MONICA
BAY
STATUTE MILES
BOTTOM CONTOURS IN FEET
BATHYTHERMOGRAM
TEMPERATURE SURFACE
DEPTH TO 60 °F IN FEET
23-24 MAY 1956
• BT STATIONS
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
45′
40′
35′
118°30′
25′
34°
55′
50′

Figure 34. Current flow between 20-80 feet, May 23-24, 1956.



SANTA MONICA BAY
1 0 1 2 3
STATUTE MILES
BOTTOM CONTOURS IN FEET
CURRENT FLOW BETWEEN
20-80 FEET
23-24 MAY 1956
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
60
300
600
45′
40′
35′
118°30′
25′
34°
55′
50′

part the gradient was quite gentle over the entire bay (Fig. 35). Closely packed isotherms near the Palos Verdes Hills may have been associated with a current to the south, but the irregularity of the water adjacent to the shore from Redondo south perhaps is more indicative of no gradient motion (Fig. 36).

Different degrees and locations of upwelling in the north, cold water in the south, and the magnitude of isothermal slopes occured on January 18, 1956, and December 29, 1955 (Figs. 37 and 38). In January, the central and southern pattern nearshore was similar to that in November. In the northern part of the bay, closely packed isotherms indicated a rather rapid flow to the south without the subsequent flow to the east noted in November. The slight gradients in the central part of the bay would result in slow or non-flow conditions, with an increased southerly drift in the southern part of the bay. Offshore, small gyrals indicative of minor convergences and divergences occurred, but they were likely too insignificant to be visually represented (Fig. 39). The isothermal pattern in the north and south part of the bay in December compared closely with that in November. However, the isothermal slope nearshore in the center of the bay was straight and constant for more than 10 miles, and must have resulted in a dominant flow to the south (Fig. 40).

The subsurface water in December and January showed dissimilarities as did the surface layers, but not to the same degree. Also, some of the temperature features were much the same in the two months. For example, in both December

Figure 35. Depth to the 55°F isotherm, May 23-24, 1956.

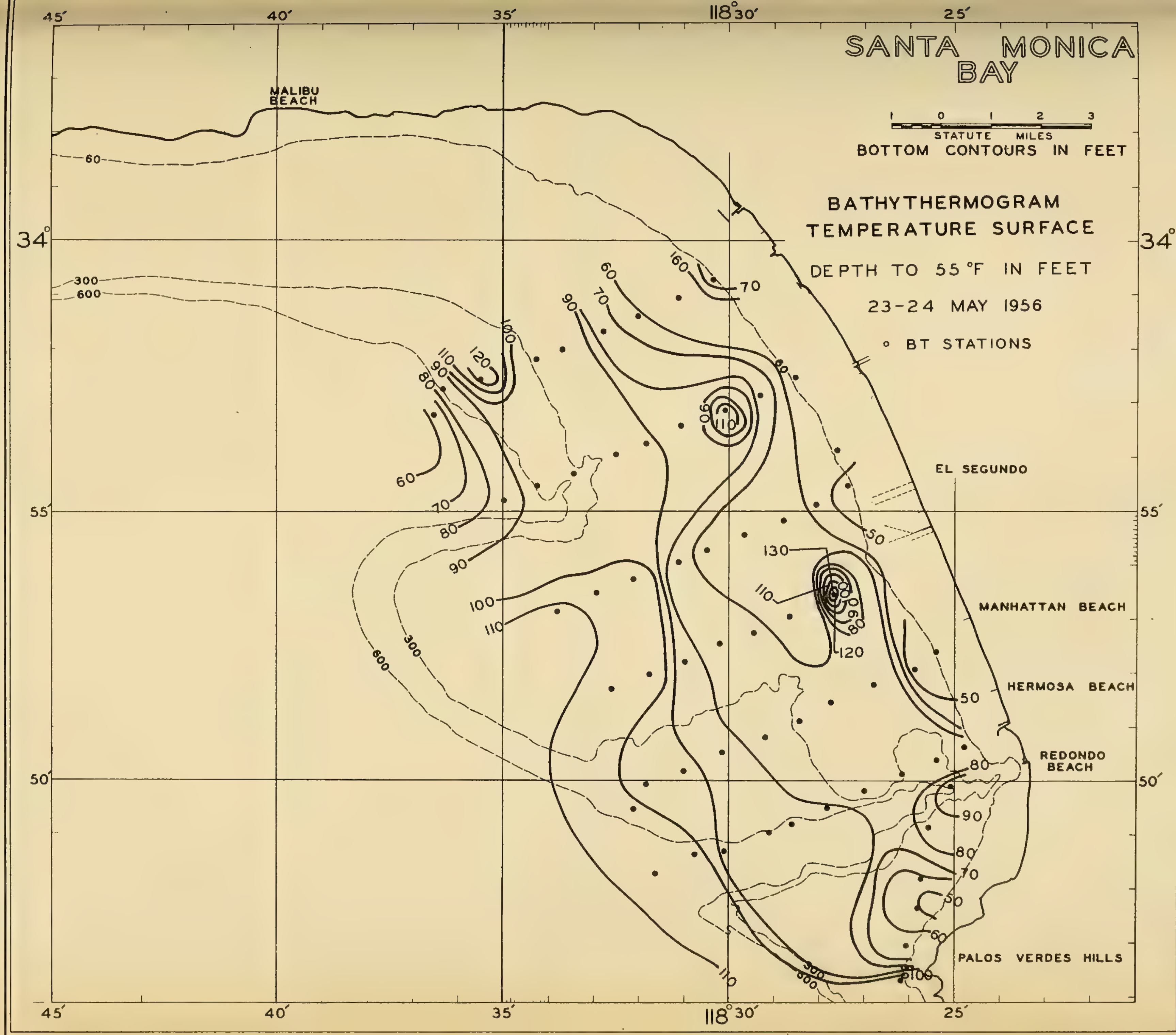
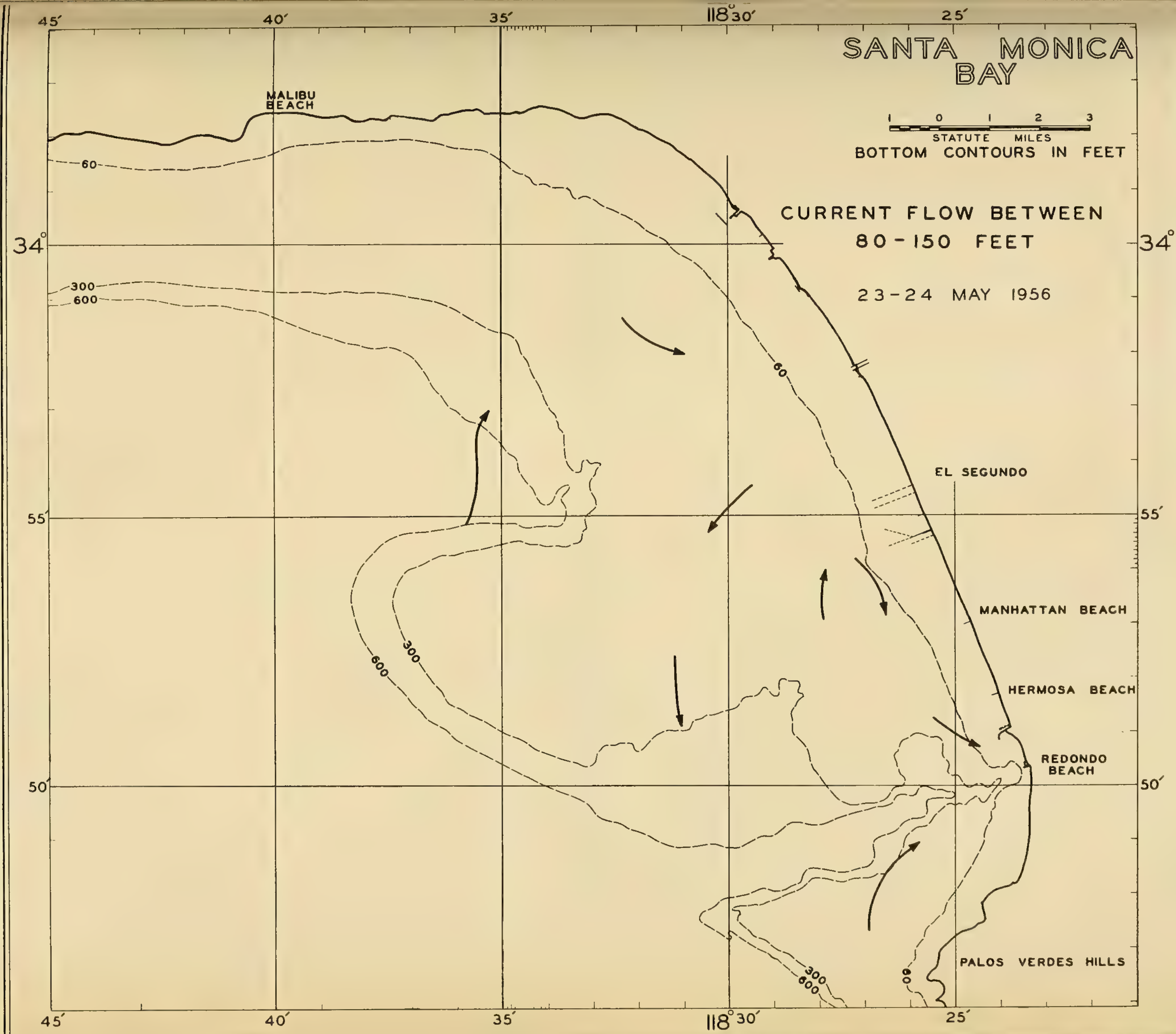

SANTA MONICA BAY
STATUTE MILES
BOTTOM CONTOURS IN FEET
BATHYTHERMOGRAM TEMPERATURE SURFACE
DEPTH TO 55 °F IN FEET
23-24 MAY 1956
° BT STATIONS
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
34°
55′
50′
45′
40′
35′
118°30′
25′

Figure 36. Current flow between 80-150 feet, May 23-24, 1956.



SANTA MONICA BAY
STATUTE MILES
1 0 1 2 3
BOTTOM CONTOURS IN FEET
CURRENT FLOW BETWEEN 80-150 FEET
23-24 MAY 1956
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
60
300
600
34°
55′
50′
45′
40′
35′
118°30′
25′

Figure 37. Depth to the $54^{\circ}F$ isotherm, January 18, 1956.

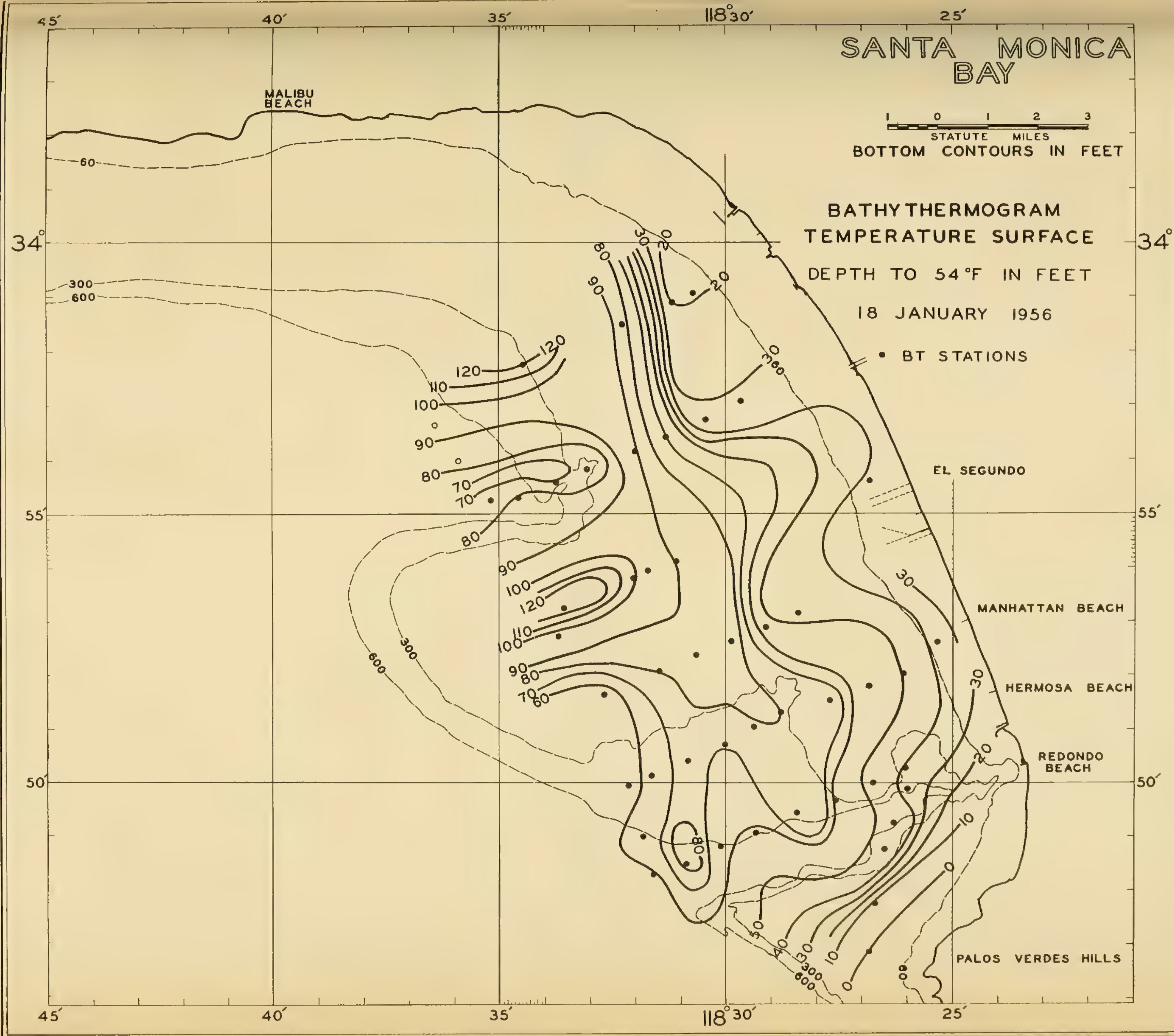

SANTA MONICA BAY
STATUTE MILES
BOTTOM CONTOURS IN FEET
BATHYTHERMOGRAM TEMPERATURE SURFACE
DEPTH TO 54°F IN FEET
18 JANUARY 1956
• BT STATIONS
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
118°30'
34°
55'
50'
45'
40'
35'
25'

Figure 38. Depth to the 57°F isotherm, December 29, 1955.

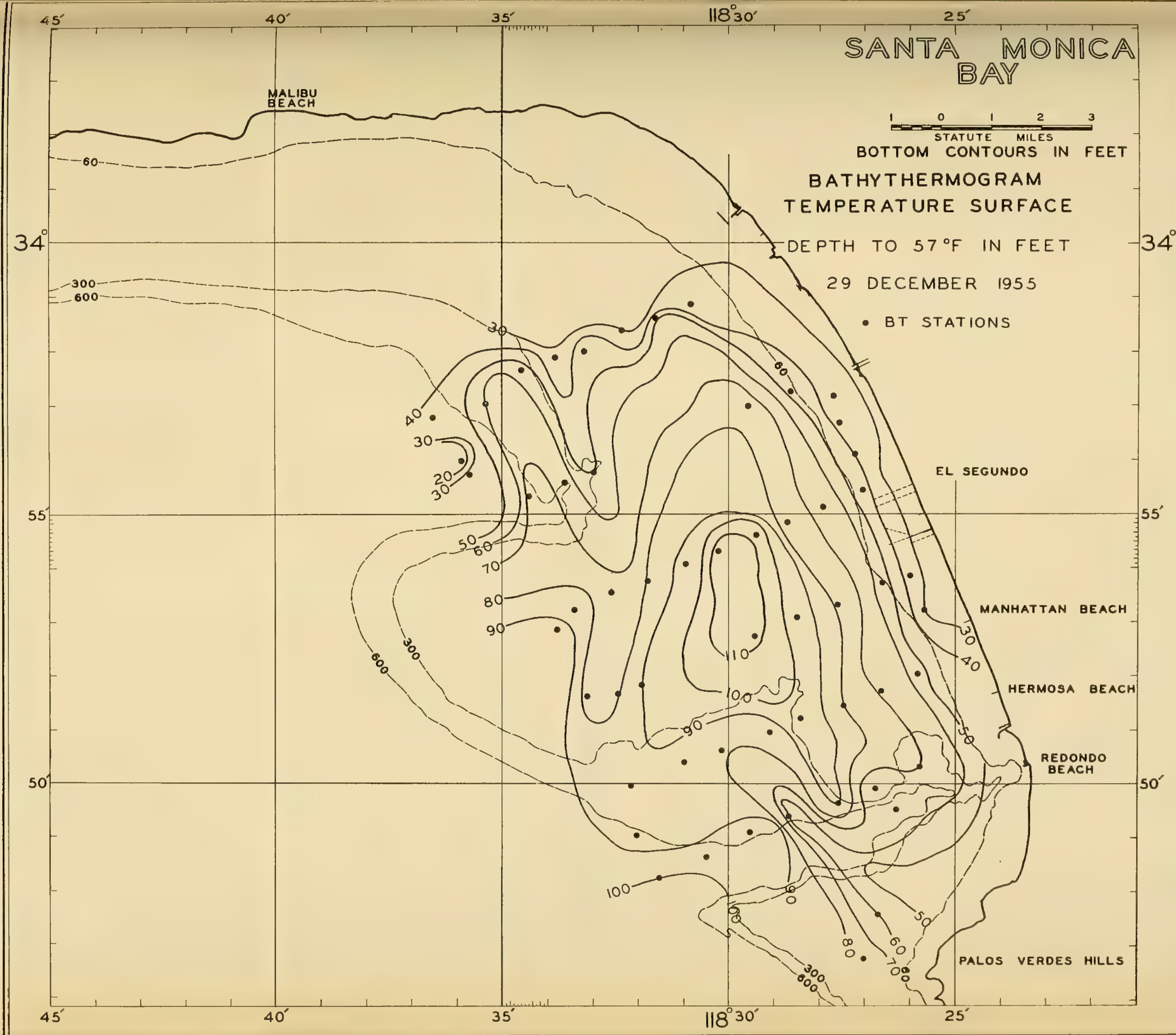

SANTA MONICA BAY
BOTTOM CONTOURS IN FEET
STATUTE MILES
BATHYTHERMOGRAM TEMPERATURE SURFACE
DEPTH TO 57°F IN FEET
29 DECEMBER 1955
• BT STATIONS
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
118°30'
34°
55'
50'
45'
40'
35'
25'

Figure 39. Current flow between 10-120 feet, January 18, 1956.

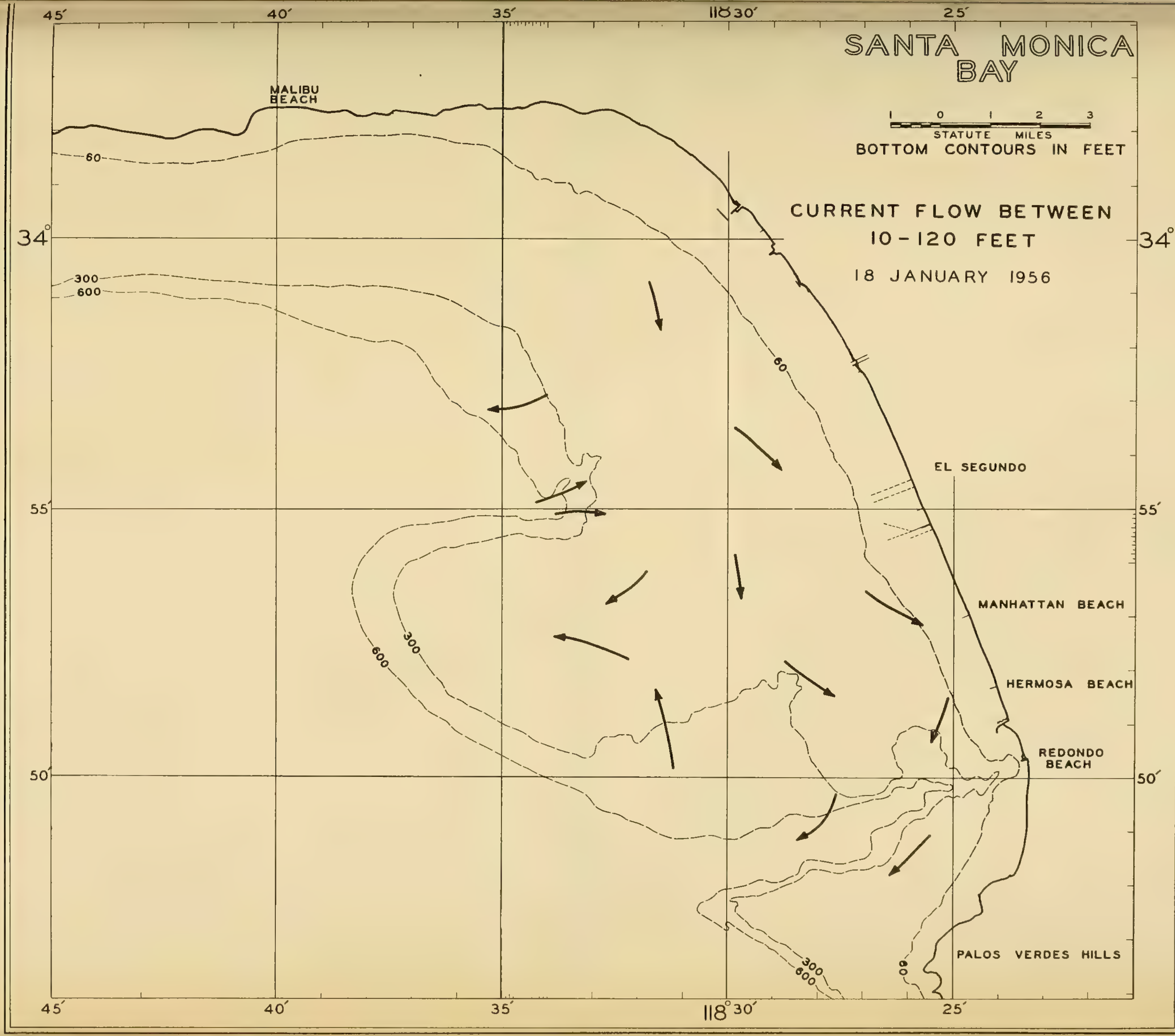
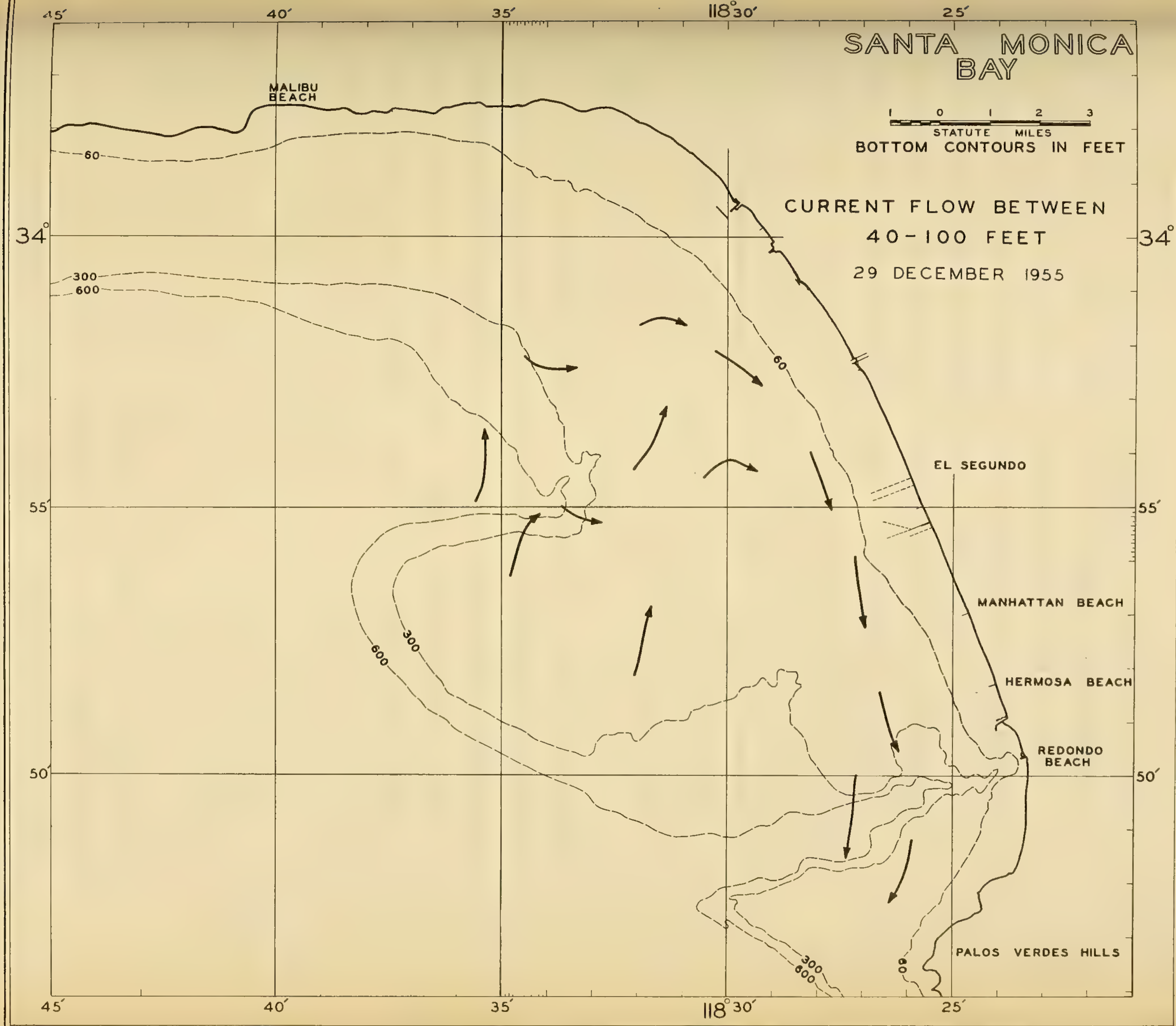

SANTA MONICA BAY
STATUTE MILES
BOTTOM CONTOURS IN FEET
CURRENT FLOW BETWEEN
10-120 FEET
18 JANUARY 1956
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
118°30′
34°

Figure 40. Current flow between 40-120 feet, December 29, 1955.


SANTA MONICA BAY
STATUTE MILES
1 0 1 2 3
BOTTOM CONTOURS IN FEET
CURRENT FLOW BETWEEN
40-100 FEET
29 DECEMBER 1955
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
60
300
600
34°
55′
50′
45′
40′
35′
118°30′
25′

and January, a subsurface convergence is indicated offshore from Redondo (Figs. 41 and 42). In January the shoreward moving water appeared to be dominant (Fig. 43), and in December it was that part of the subsurface unit moving to the south along shore which must have had the higher velocity (Fig. 44). In each case, however, there was no reflection of this action in the surface layers. In January, offshore gyrals and a steep thermal slope in the northern part of the bay matched conditions in the surface layers. The December subsurface temperature topography corresponded to that of the surface unit in the nearshore area and in the north where slopes were indicative of southerly flow along shore and a flow towards the east from offshore.

The temperature patterns for April 25, 1956, and February 22, 1956, show two differing conditions in which water may be brought in and out of the bay (Figs. 45 and 46). On April 25, water should have flowed rather gently into the bay in the north toward Santa Monica followed by a swing to the south to Playa del Rey, and then seaward in a southwesterly direction opposite Hyperion. As this flow entered the area of flat gradients in the south, any current flow should have been due to wind drift, which in this case would have been shoreward (Fig. 47). In February, a similar cold water area existed in the north, but in this instance, the isotherms were closely packed in the central part of the bay opposite Hyperion. Water motion should have been rather strong toward the central shore of Santa Monica Bay followed by a turn to the south within one or two miles of shore (Fig. 48). In each case, the flow

Figure 41. Depth to the 55°F isotherm, December 29, 1955.

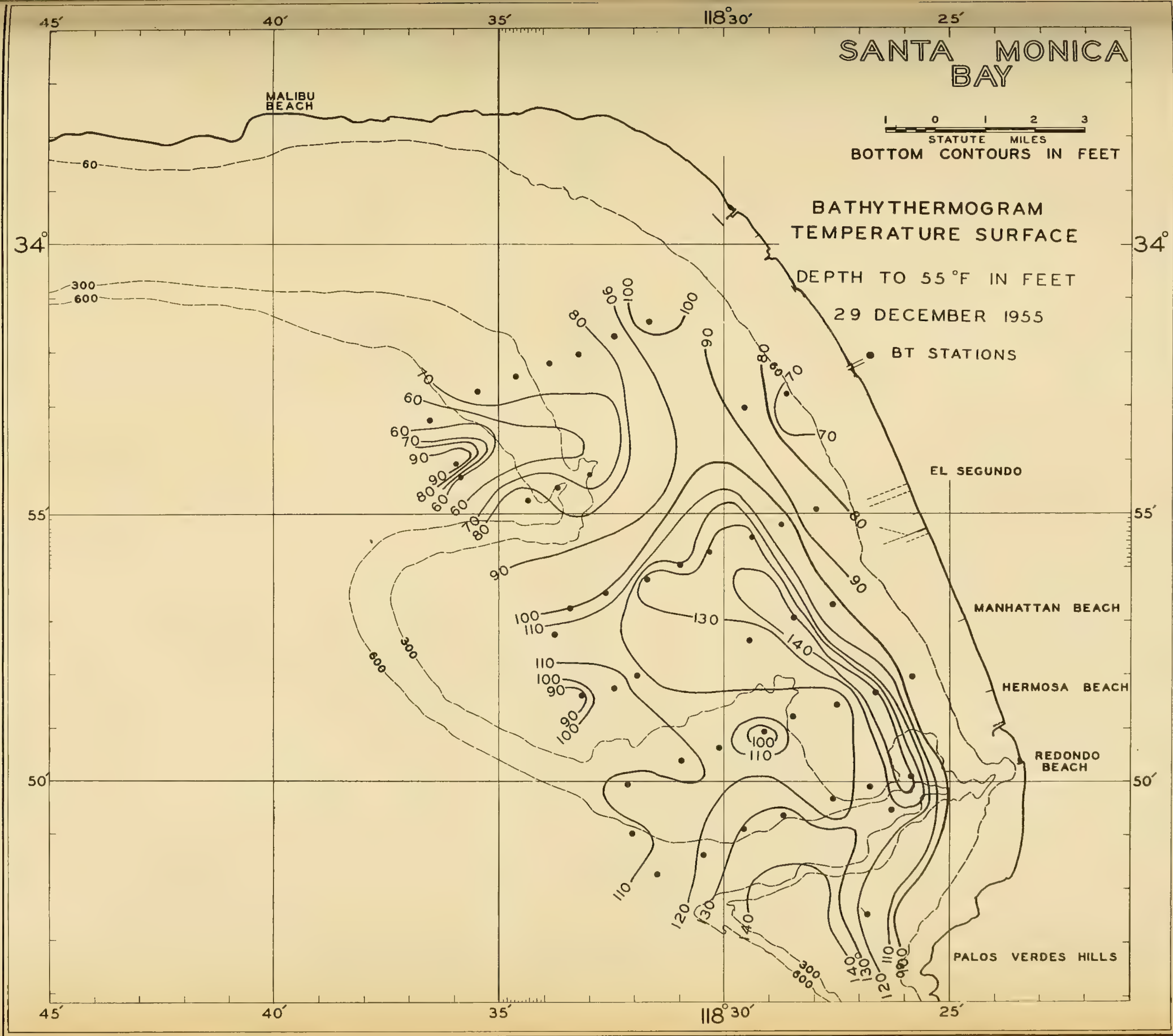

SANTA MONICA BAY
STATUTE MILES
BOTTOM CONTOURS IN FEET
BATHYTHERMOGRAM TEMPERATURE SURFACE
DEPTH TO 55 °F IN FEET
29 DECEMBER 1955
BT STATIONS
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
118°30′
34°
55′
50′
45′
40′
35′
25′

Figure 42. Depth to $52^{O}F$ isotherm, January 18, 1956.

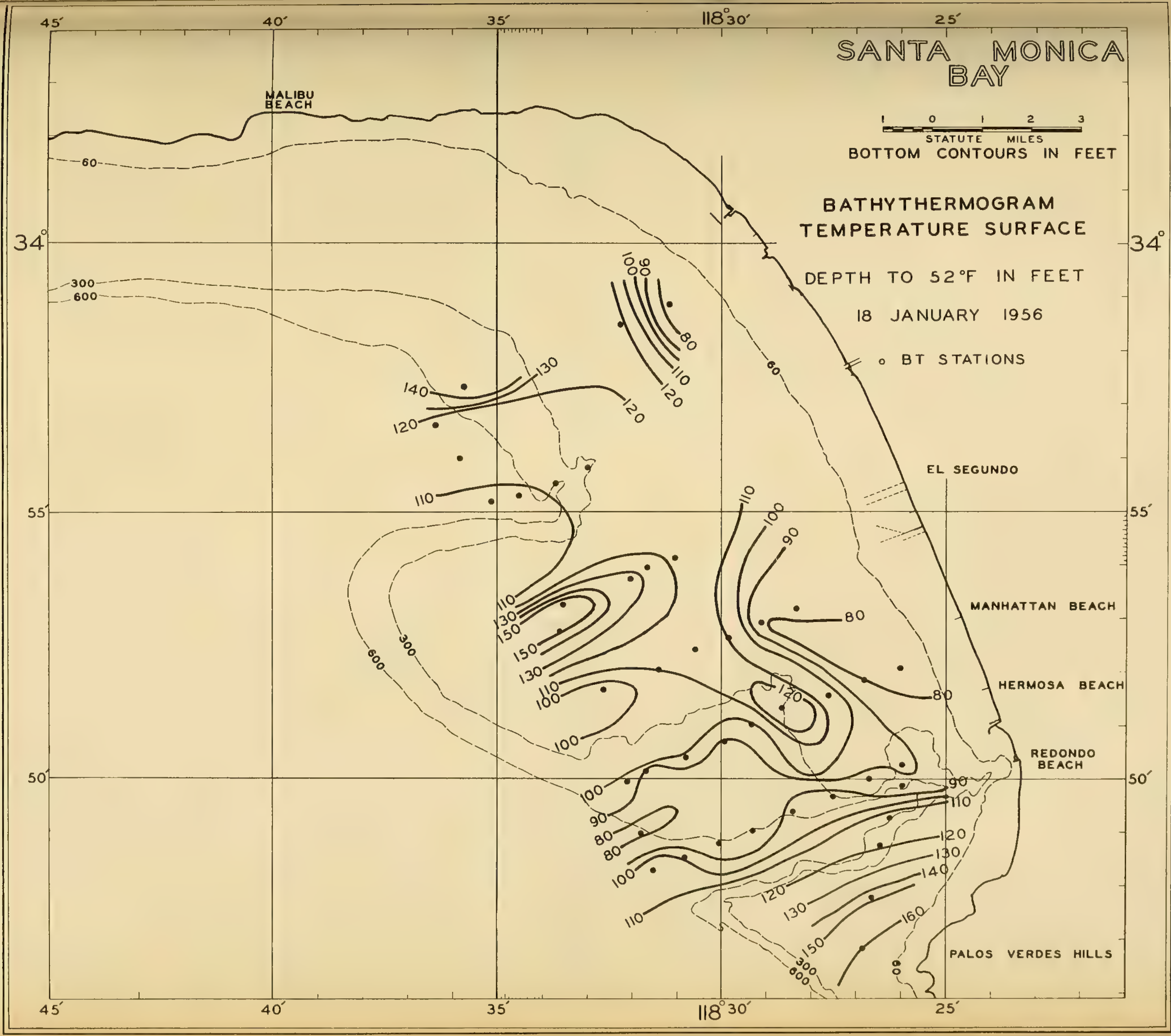

SANTA MONICA BAY
STATUTE MILES
BOTTOM CONTOURS IN FEET
BATHYTHERMOGRAM TEMPERATURE SURFACE
DEPTH TO 52°F IN FEET
18 JANUARY 1956
o BT STATIONS
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
45′
40′
35′
118°30′
25′
34°
55′
50′

Figure 43. Current flow between 120-150 feet, January 18, 1956.

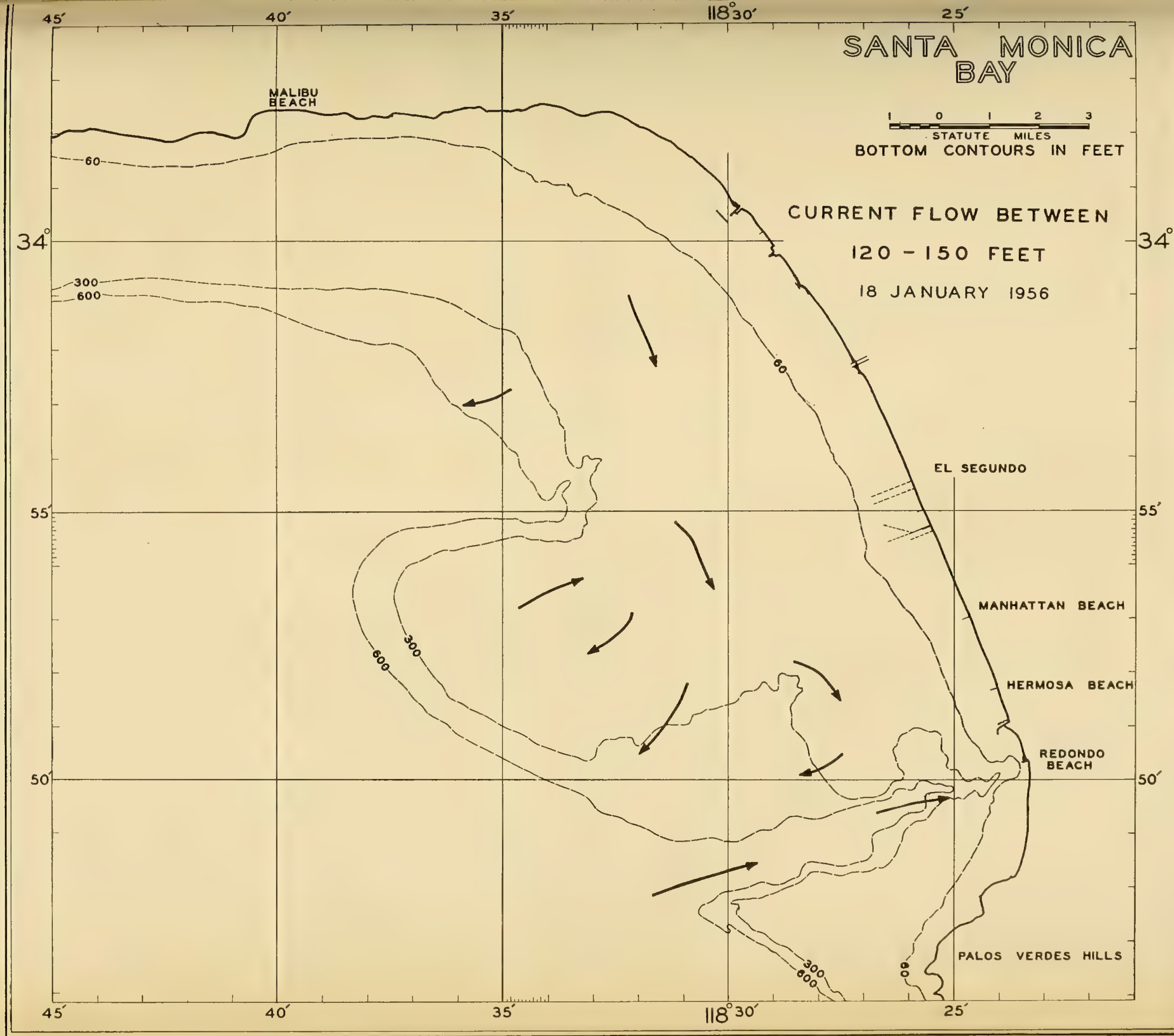
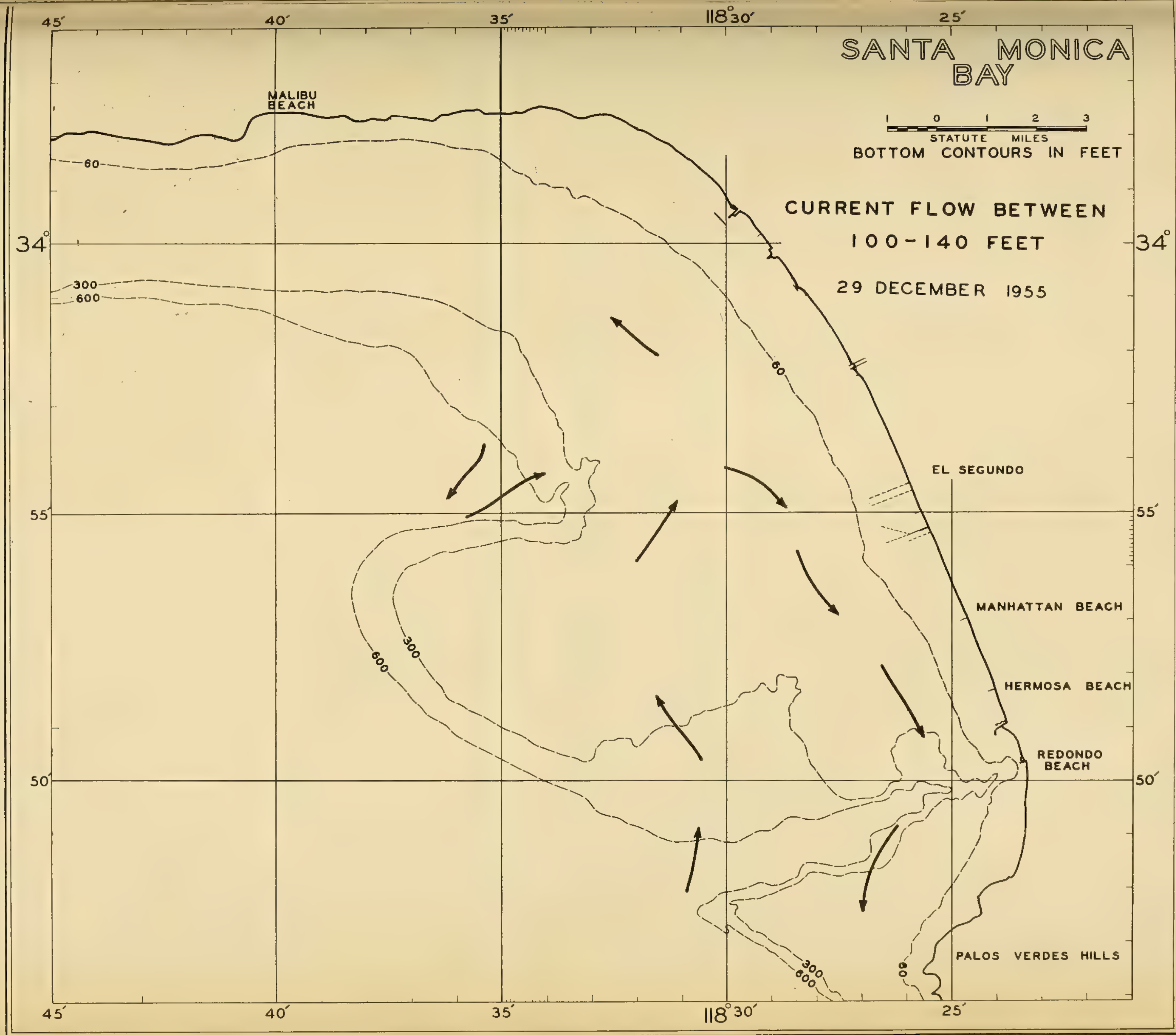
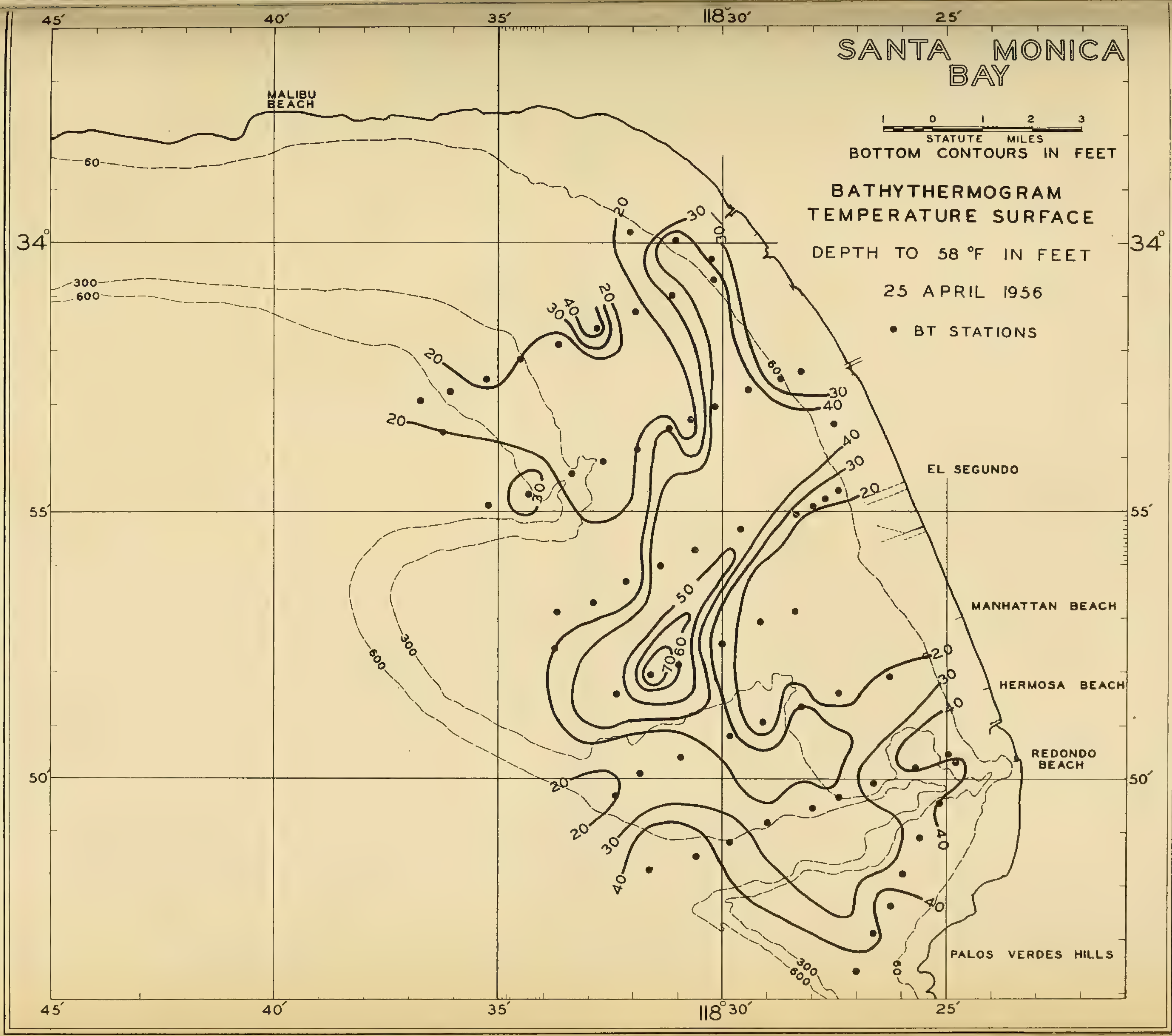

SANTA MONICA BAY
STATUTE MILES
BOTTOM CONTOURS IN FEET
CURRENT FLOW BETWEEN
120 - 150 FEET
18 JANUARY 1956
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS

Figure 44. Current flow between 100-140 feet, December 29, 1955.



SANTA MONICA BAY
1 0 1 2 3
STATUTE MILES
BOTTOM CONTOURS IN FEET
CURRENT FLOW BETWEEN
100-140 FEET
29 DECEMBER 1955
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
60
300
600
45′
40′
35′
118°30′
25′
34°
55′
50′

Figure 45. Depth to $58^{o}F$ isotherm, April 25, 1956.



SANTA MONICA BAY
STATUTE MILES
BOTTOM CONTOURS IN FEET
BATHYTHERMOGRAM TEMPERATURE SURFACE
DEPTH TO 58 °F IN FEET
25 APRIL 1956
• BT STATIONS
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
118°30′
34°
55′
50′
45′
40′
35′
25′

Figure 46. Depth to the $55^{o}F$ isotherm, February 22, 1956.

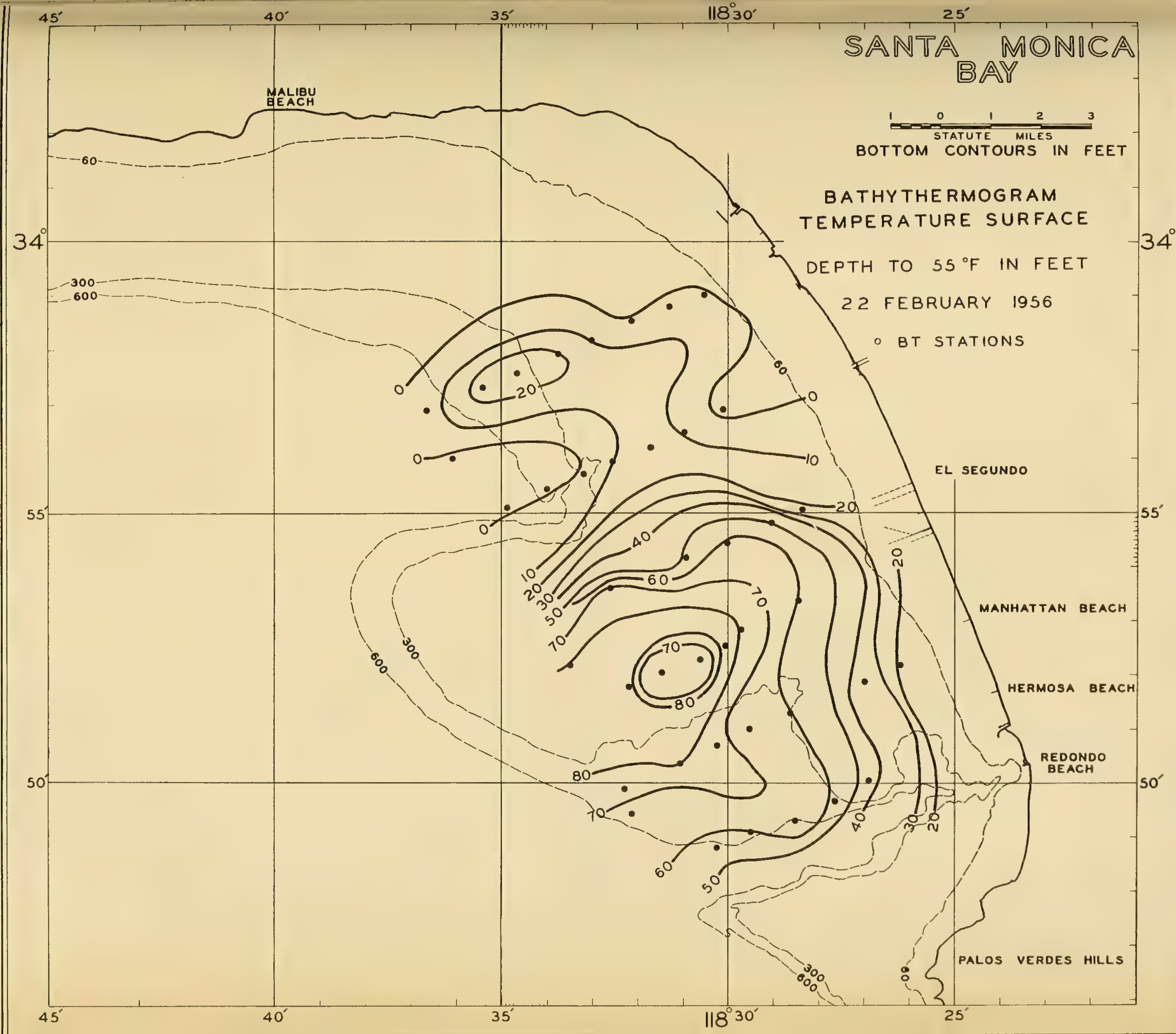

SANTA MONICA BAY
STATUTE MILES
BOTTOM CONTOURS IN FEET
BATHYTHERMOGRAM TEMPERATURE SURFACE
DEPTH TO 55 °F IN FEET
22 FEBRUARY 1956
o BT STATIONS
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
118°30′
34°
55′
50′
45′
40′
35′
25′

Figure 47. Current flow between 20-70 feet, April 25, 1956.

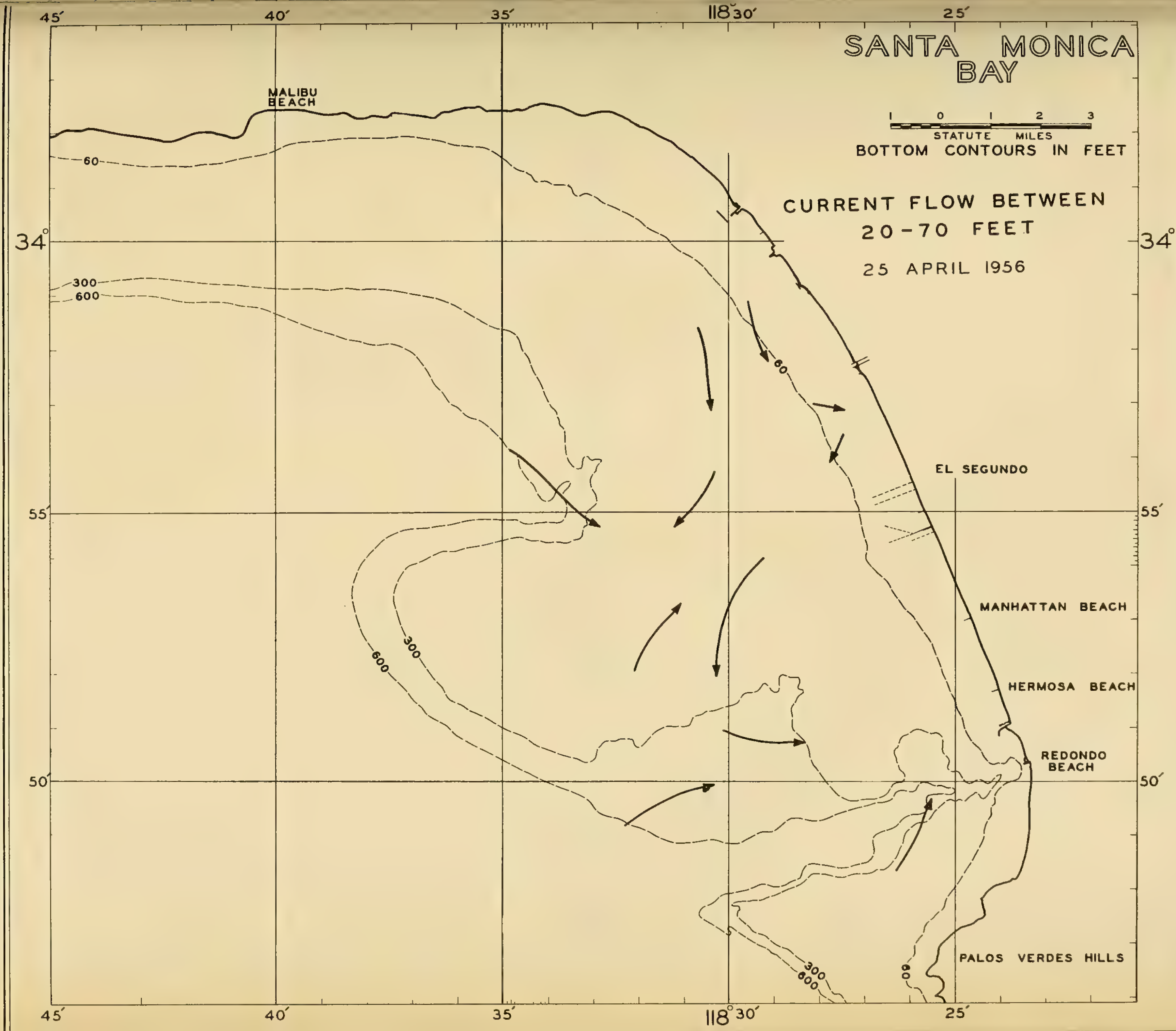
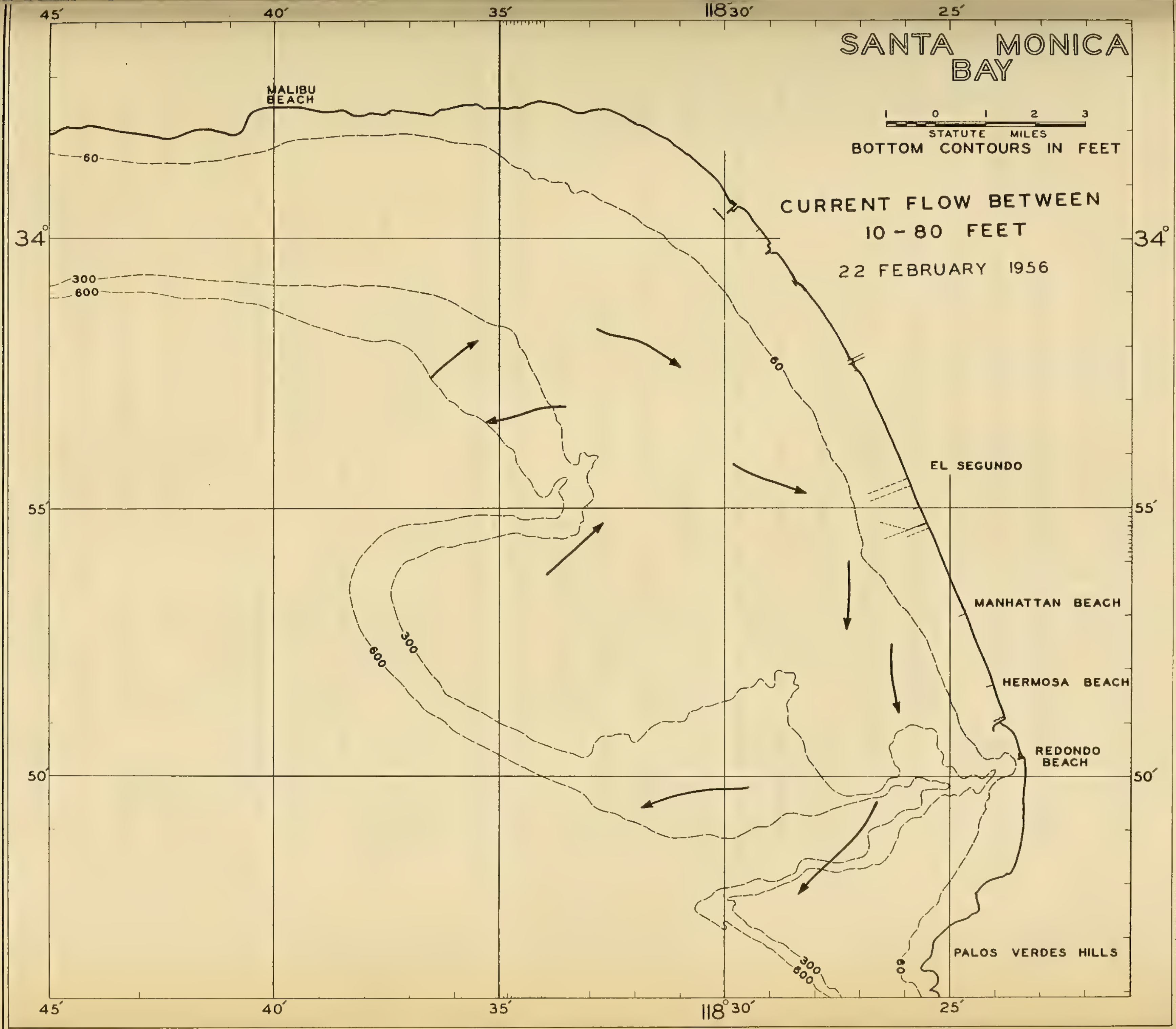

SANTA MONICA BAY
1 0 1 2 3
STATUTE MILES
BOTTOM CONTOURS IN FEET
CURRENT FLOW BETWEEN
20-70 FEET
25 APRIL 1956
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
60
300
600
45′
40′
35′
118°30′
25′
34°
55′
50′

Figure 48. Current flow between 10-80 feet, February 22, 1956.


SANTA MONICA BAY
1 0 1 2 3
STATUTE MILES
BOTTOM CONTOURS IN FEET
CURRENT FLOW BETWEEN
10 - 80 FEET
22 FEBRUARY 1956
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
60
300
600
45′
40′
35′
118°30′
25′
34°
55′
50′

simulates a large gyral, but the introduction and removal of water is restricted to only part of the bay.

The April subsurface temperature distribution was more indicative of water motion than that in the upper layers (Fig. 49). In this month there was an indication of a divergence opposite Playa del Rey where the isotherms showed a flow entering from the west to within three miles of shore and then diverging to the north and south (Fig. 50). Both of the slopes parallel to the shore were strong and continuous, and likely developed dominant flows out of the bay in the two directions. The subsurface topography in February showed an almost completely different pattern from the surface water (Fig. 51). There was a similar packing of the isotherms in the central part of the bay which may have resulted in a shoreward transport, but the general motion was then to the north following the warmer mass of water near shore (Fig. 52). This is not an uncommon feature of the water in the bay, and certainly must indicate the immediate reaction of the uppermost water layers to specific meteorologic conditions.

The thermal pattern for March 21, 1956 shows the only temperature distribution that departs from that normal to the winter (Fig. 53). This is also the only clear cut case where any data show the introduction of water from the south into the bay and the escape of water to the north. The flat gradient offshore would allow drift toward the east to within two miles of shore where the strong northerly flow was present. Drift cards released on this day all landed to the north of their point of origin, confirming this pattern. This

Figure 49. Depth to $53^{o}F$ isotherm, April 25, 1956.

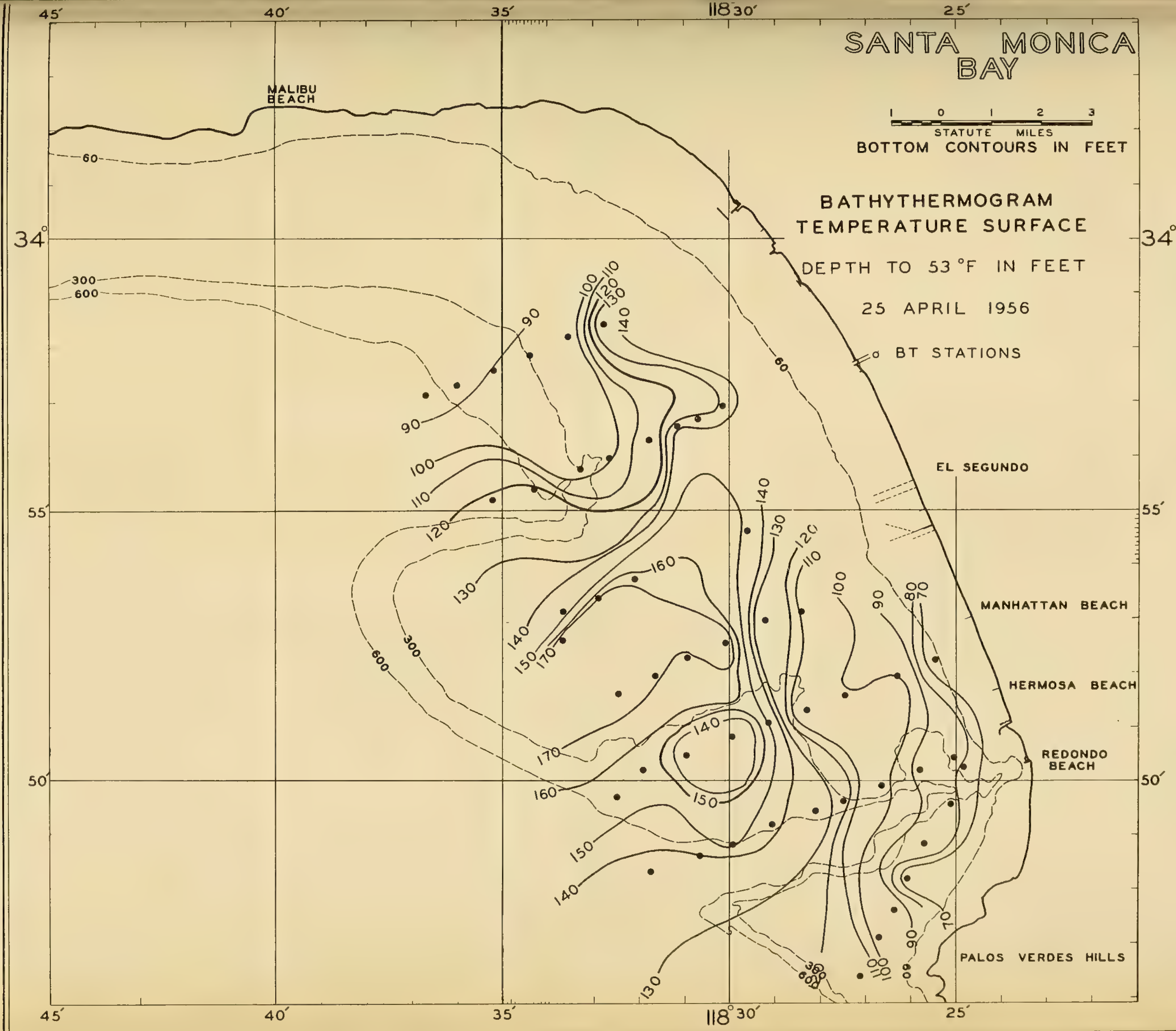
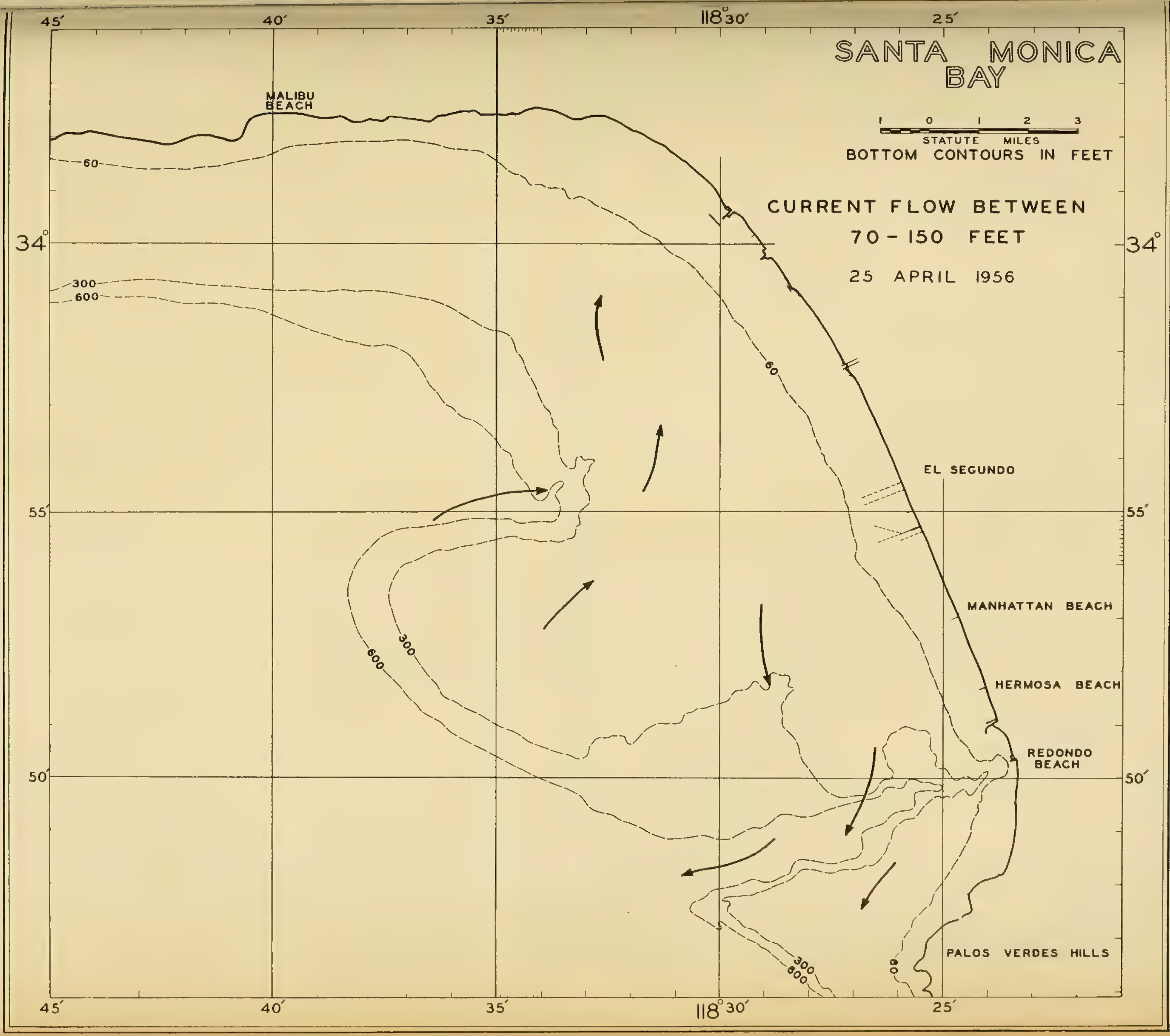

SANTA MONICA BAY
STATUTE MILES
BOTTOM CONTOURS IN FEET
BATHYTHERMOGRAM TEMPERATURE SURFACE
DEPTH TO 53 °F IN FEET
25 APRIL 1956
BT STATIONS
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS

Figure 50. Current flow between 70-150 feet, April 25,1956.



SANTA MONICA BAY
1 0 1 2 3
STATUTE MILES
BOTTOM CONTOURS IN FEET
CURRENT FLOW BETWEEN
70 - 150 FEET
25 APRIL 1956
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
60
300
600
34°
55′
50′
45′
40′
35′
118°30′
25′

Figure 51. Depth to 52°F isotherm, February 22, 1956.

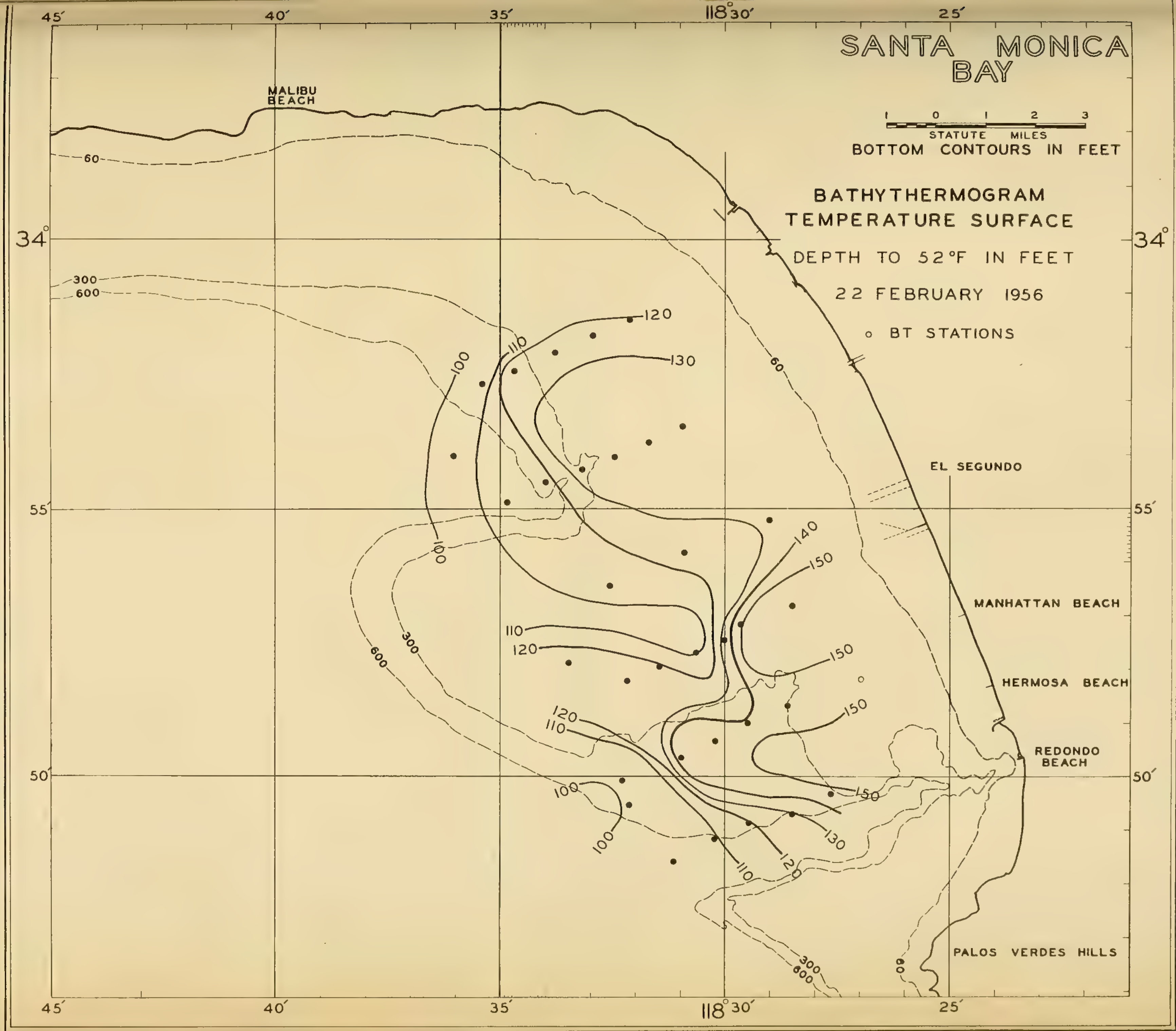
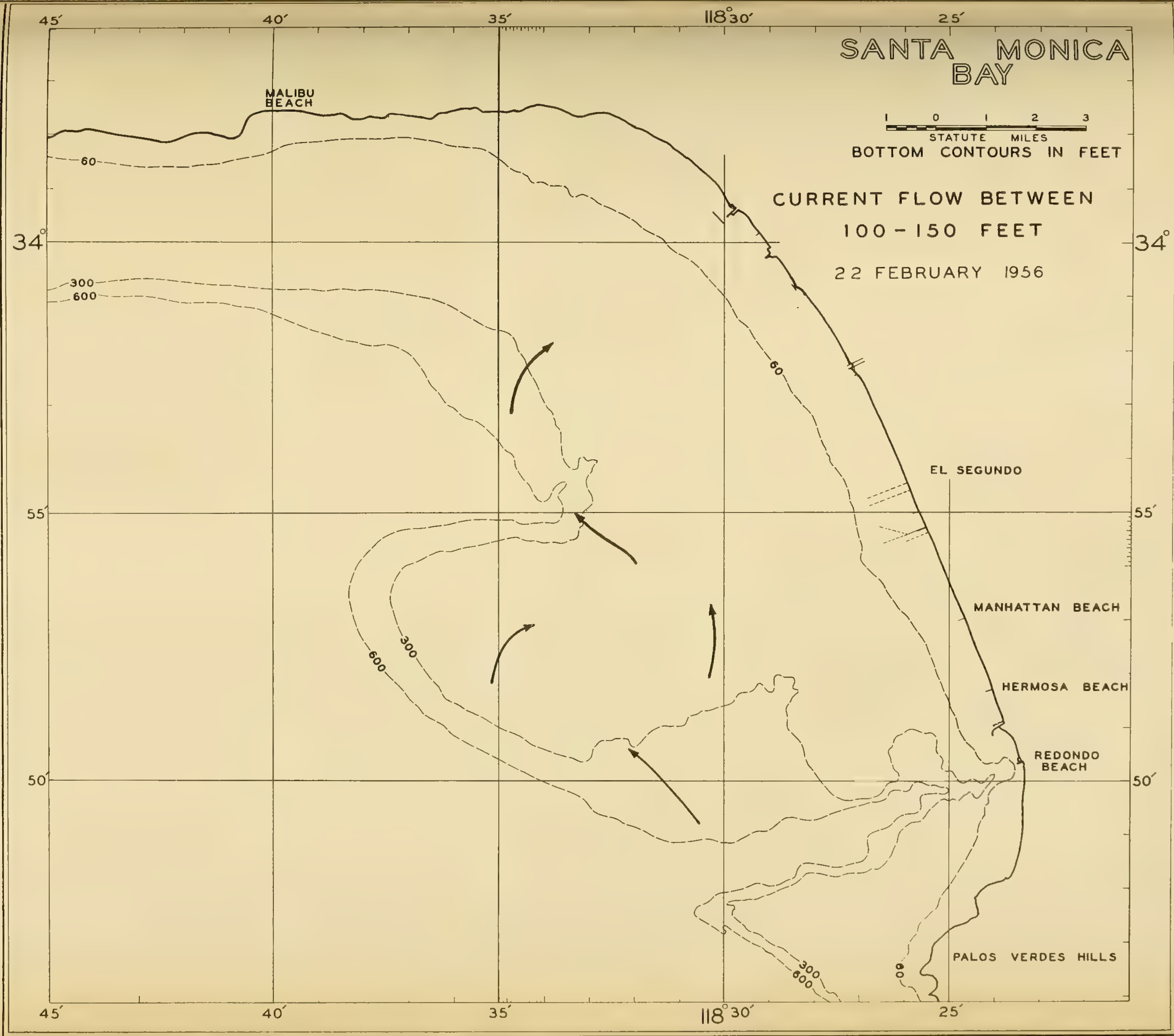

SANTA MONICA BAY
STATUTE MILES
BOTTOM CONTOURS IN FEET
BATHYTHERMOGRAM
TEMPERATURE SURFACE
DEPTH TO 52°F IN FEET
22 FEBRUARY 1956
BT STATIONS
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS

Figure 52. Current flow between 100-150 feet,
February 22, 1956



SANTA MONICA BAY
1 0 1 2 3
STATUTE MILES
BOTTOM CONTOURS IN FEET
CURRENT FLOW BETWEEN
100 - 150 FEET
22 FEBRUARY 1956
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
60
300
600
45′
40′
35′
118°30′
25′
34°
55′
50′

Figure 53. Depth to 56°F isotherm, March 21, 1956


SANTA MONICA BAY
STATUTE MILES
BOTTOM CONTOURS IN FEET
BATHYTHERMOGRAM TEMPERATURE SURFACE
DEPTH TO 56 °F IN FEET
21 MARCH 1956
• BT STATIONS
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
118°30′
34°
55′
50′
45′
40′
35′
25′

is one of the simplest thermal patterns occurring and yet is the one showing the most striking effects of flow resulting from thermal slopes.

Again in March there was a marked dissimilarity between the surface and subsurface temperature topographies. Whereas in the upper mixed zone there was warm water offshore and adjacent to the coast, with a cooler mass lying between, the subsurface water was more complex in its temperature distribution and the cool water was next to the coast (Fig. 54). In this case, the water motion must have been into the bay through the northern portion and out of the bay to the south, almost in complete opposition to the motion in the Surface Water Unit. As noted previously, such a condition is not unique and is to be expected when ocean and meteorological situations combine to give strong thermoclines and definite wind drift patterns in the upper water layers.

Summer. The summer season, i.e., the months when the nearshore waters of Santa Monica Bay are warmer than those offshore, begins in June and extends through October. These are also the months when greater differences are noted between the surface and subsurface water units. The upper layers during this season have dominant flows to the north with a varying degree of fluctuation due to man-made contribution, solar insolation, and wind. The subsurface patterns, on the other hand, indicate northerly drift in two months, southerly drift during another, and drifts in different directions in the other two months. More convergences and divergences occur in the bay waters during these months, and on the whole, the

Figure 54. Depth to 54°F isotherm, March 21, 1956


SANTA MONICA BAY
1 0 1 2 3
STATUTE MILES
BOTTOM CONTOURS IN FEET
BATHYTHERMOGRAM TEMPERATURE SURFACE
DEPTH TO 54 °F IN FEET
21 MARCH 1956
° BT STATIONS
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
34°
55′
50′
45′
40′
35′
118°30′
25′
60
70
80
90
100
110
300
600

temperature topographies are more complex than in the colder months of the year. This, of course, is to be expected due to greater density differences between the surface and subsurface water in the warmer season.

A typical surface is shown in Figure 55, which depicts the 61°F isothermal surface on July 6, 1955. The normal upwelling pattern occurred in the northern part of the bay, indicating a flow into the area off Santa Monica. A convergence was found off Venice coupled with a divergence to the south opposite El Segundo. Water was obviously leaving the bay to the south, and the flat gradient offshore was indicative of wind dominance over the drift of the water. The subsurface topography on this day had a nearly identical pattern which shows the stability of water motion over the continental shelf following extended periods of stable meteorological conditions (Fig. 56).

The constant nature of the cold water along the Malibu shore, and the variation from simple to highly complex temperature surfaces that occur over short periods of time are shown in Figures 57, 58, 59, 60, 61, 62, and 63, which show thermal topographies for August 10, 18, and 24, 1955. On each day, the colder units discussed previously as being in a more or less steady state condition in the north and south borders of the bay were dominantly present. On August 18, the upwelling water from the north extended into the bay as far south as Manhattan Beach; a temperature pattern which repeated itself in March 1956. On each occasion, winds stronger than Force 4 had blown quite steadily for the two to three preceding days.

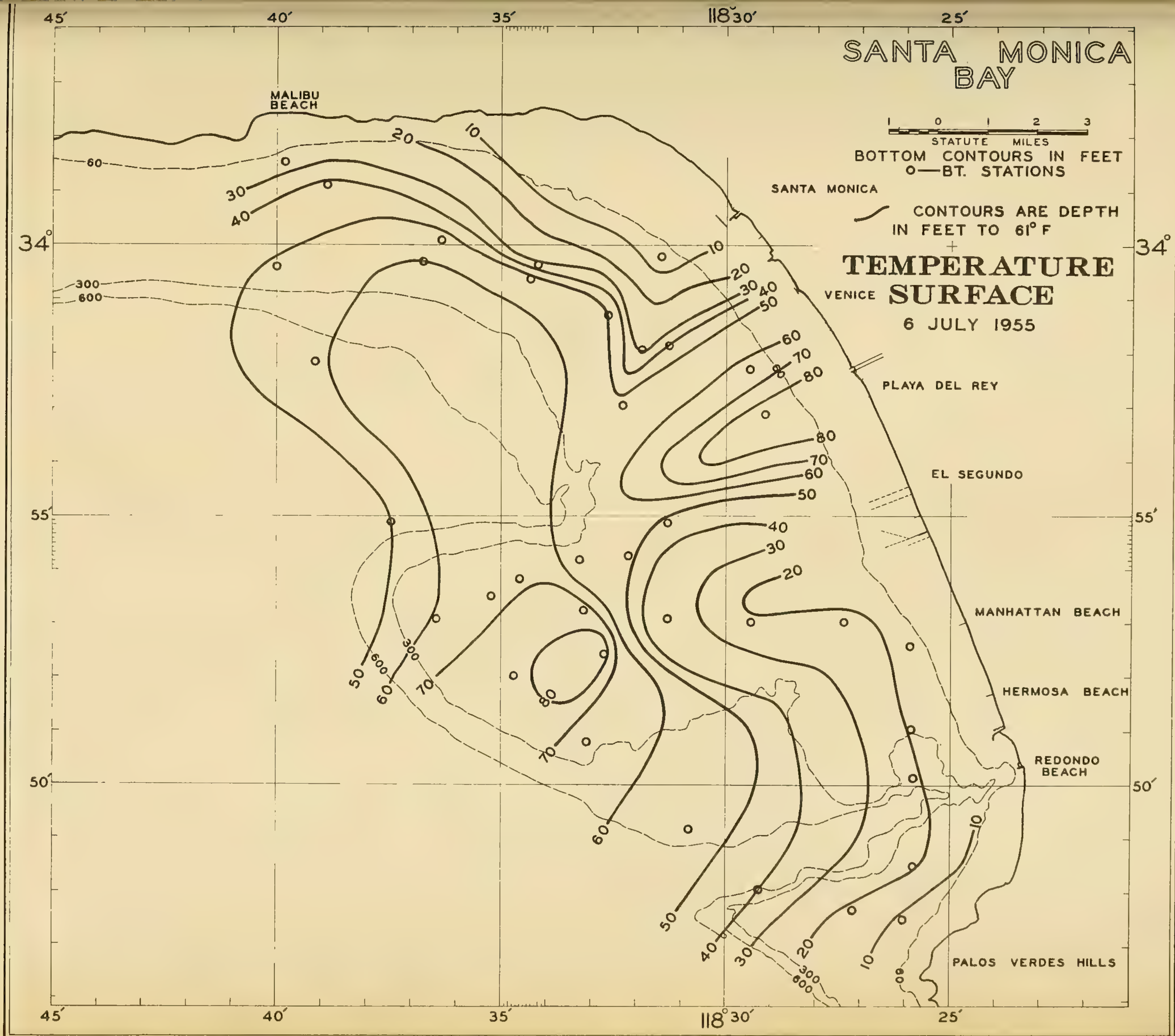

SANTA MONICA BAY
STATUTE MILES
BOTTOM CONTOURS IN FEET
O—BT. STATIONS
CONTOURS ARE DEPTH IN FEET TO 61° F
TEMPERATURE SURFACE
6 JULY 1955
MALIBU BEACH
SANTA MONICA
VENICE
PLAYA DEL REY
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
34°
55′
50′
45′
40′
35′
118°30′
25′

Figure 56. Depth to $55^{\circ}F$ isotherm, July 6, 1955

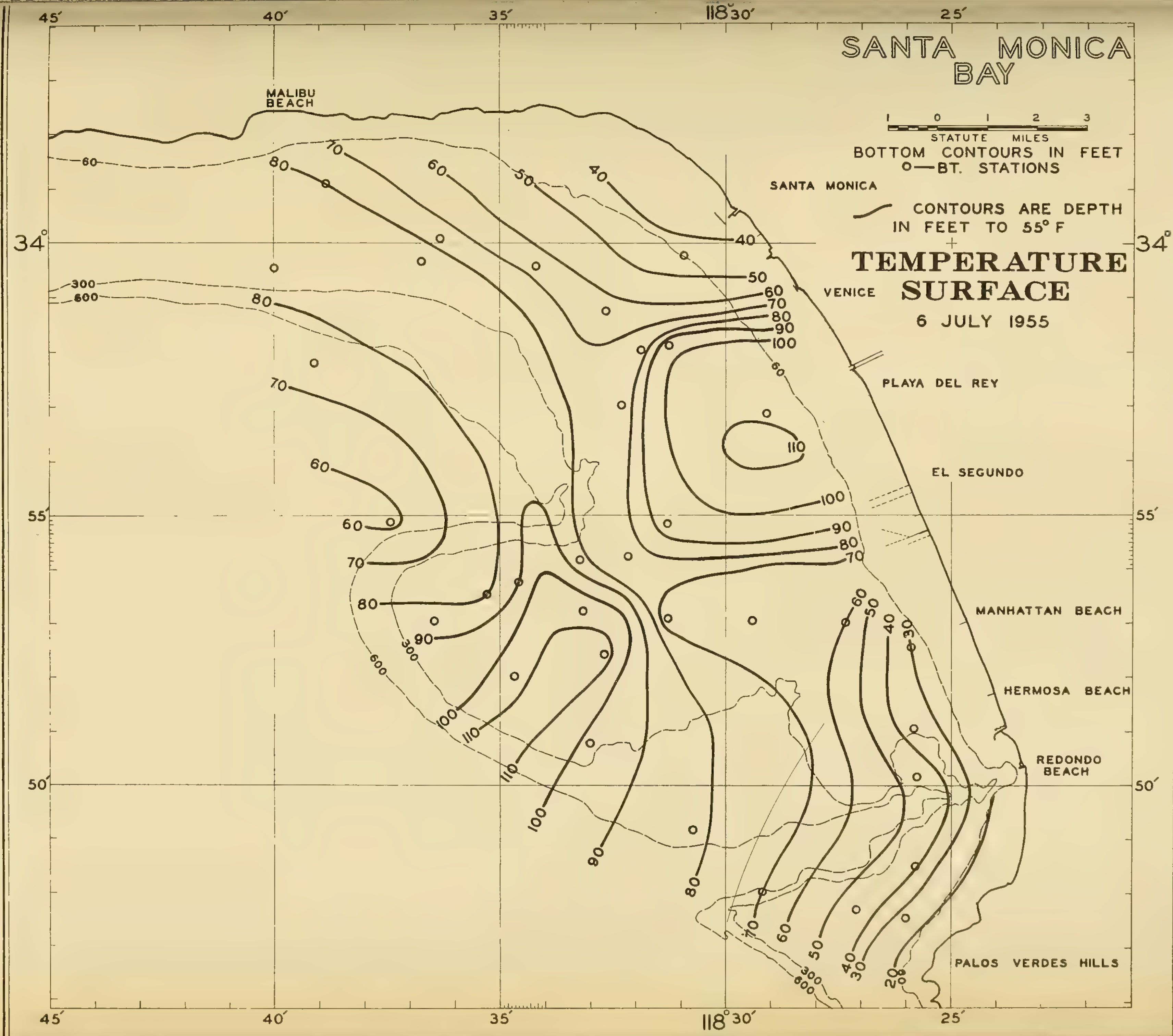

SANTA MONICA BAY
TEMPERATURE SURFACE
6 JULY 1955
CONTOURS ARE DEPTH IN FEET TO 55° F
BOTTOM CONTOURS IN FEET
o—BT. STATIONS
STATUTE MILES
1 0 1 2 3
MALIBU BEACH
SANTA MONICA
VENICE
PLAYA DEL REY
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
34°
55′
50′
45′
40′
35′
118°30′
25′

Figure 57. Depth to 62°F isotherm, August 10, 1955

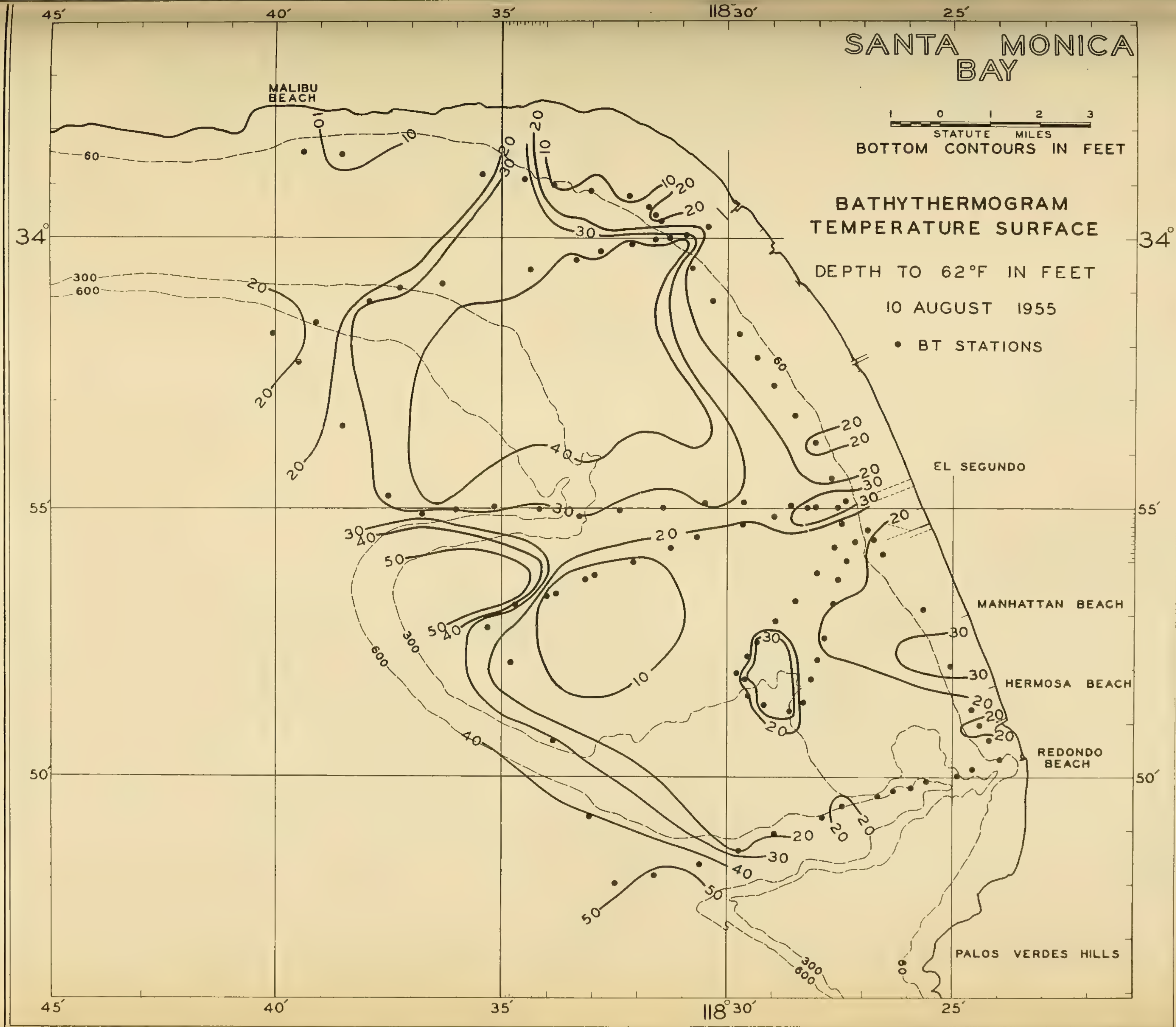

SANTA MONICA BAY
STATUTE MILES
BOTTOM CONTOURS IN FEET
BATHYTHERMOGRAM TEMPERATURE SURFACE
DEPTH TO 62°F IN FEET
10 AUGUST 1955
BT STATIONS
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
34°
55′
50′
45′
40′
35′
118°30′
25′

Figure 58. Depth to $53^{\circ}F$ isotherm, August 10, 1955

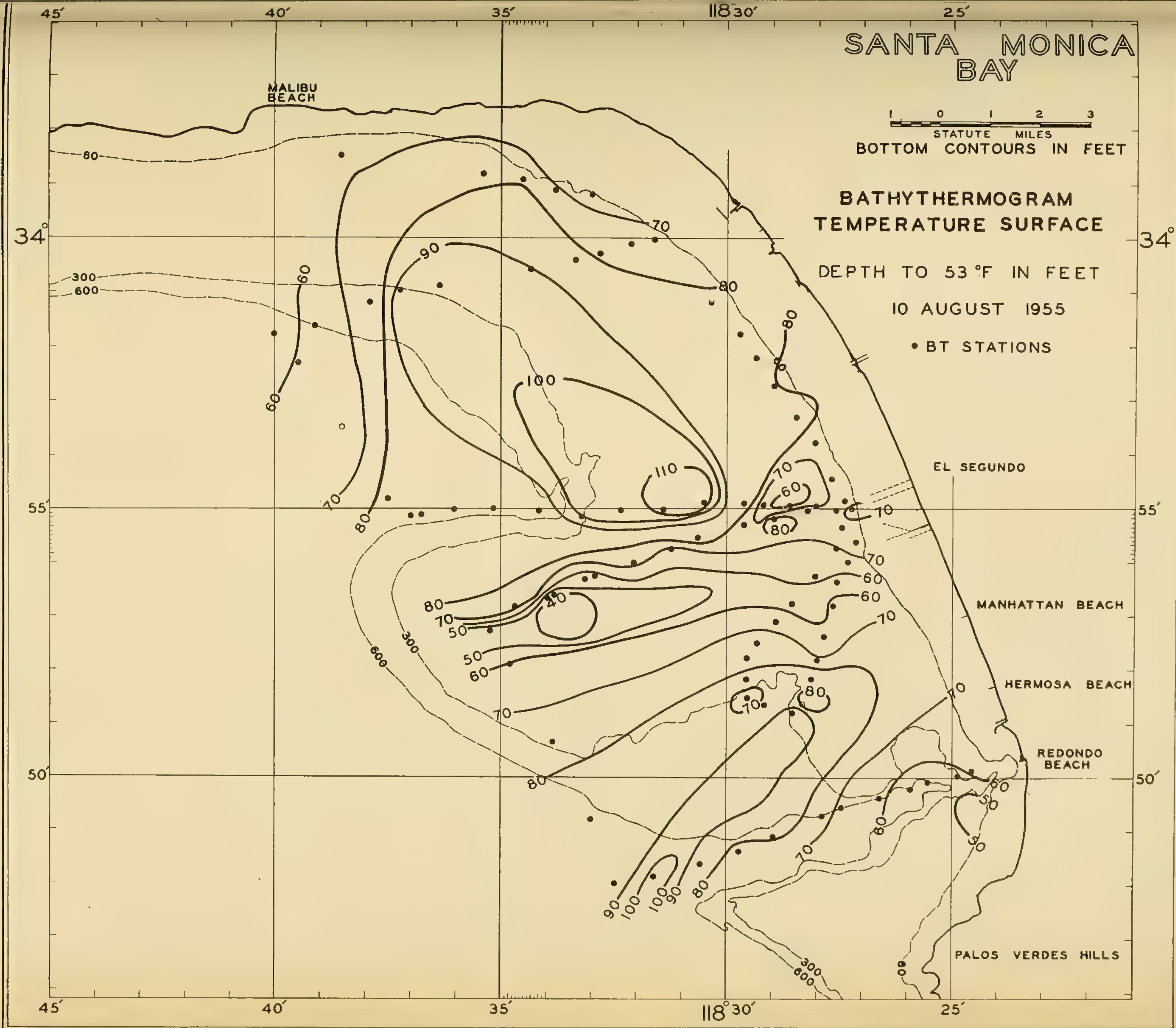

SANTA MONICA BAY
STATUTE MILES
BOTTOM CONTOURS IN FEET
BATHYTHERMOGRAM TEMPERATURE SURFACE
DEPTH TO 53 °F IN FEET
10 AUGUST 1955
• BT STATIONS
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
118°30′
34°
55′
50′
45′
40′
35′
25′

Figure 59. Depth to 62°F isotherm, August 18, 1955

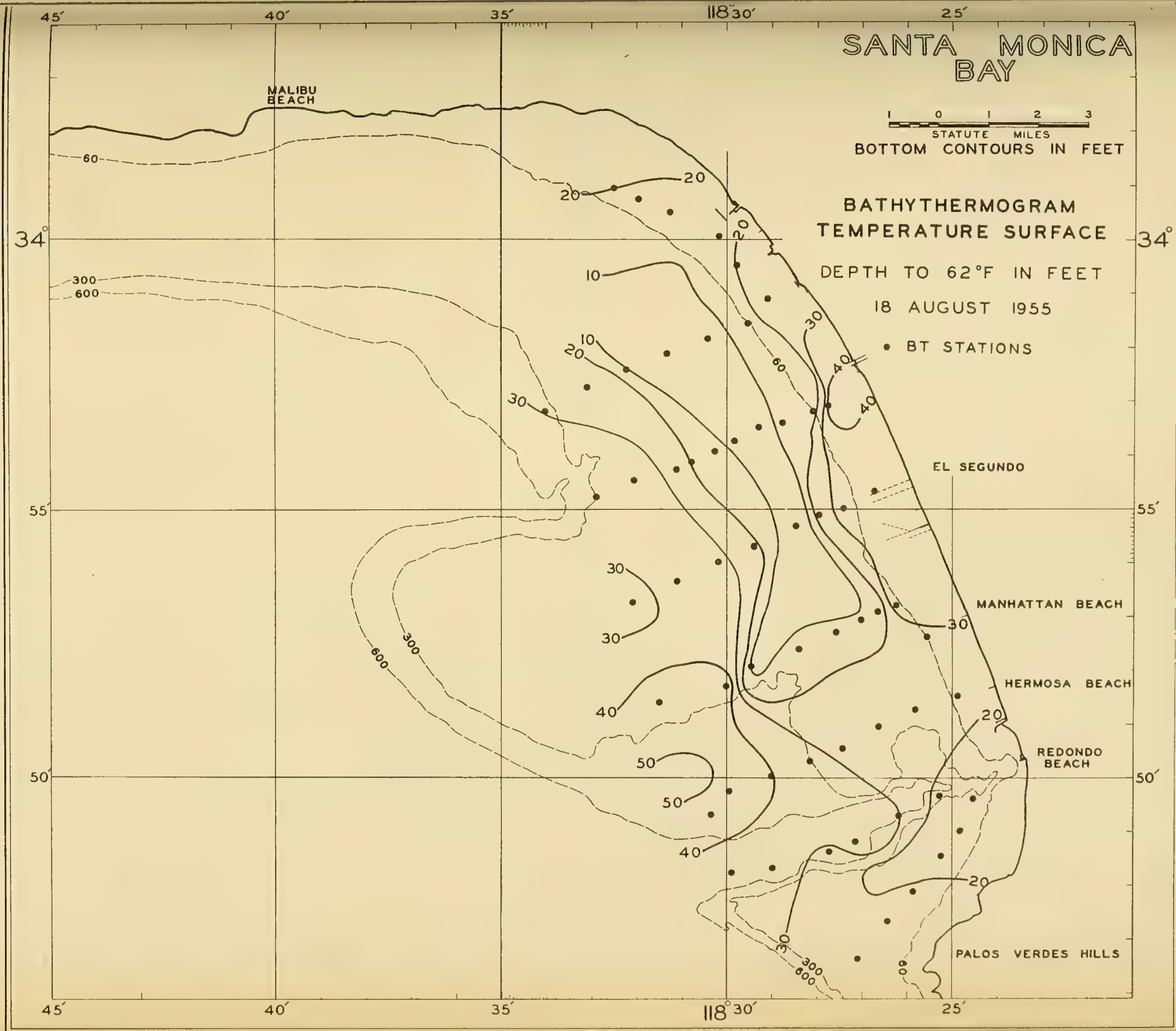

SANTA MONICA BAY
STATUTE MILES
1 0 1 2 3
BOTTOM CONTOURS IN FEET
BATHYTHERMOGRAM TEMPERATURE SURFACE
DEPTH TO 62°F IN FEET
18 AUGUST 1955
• BT STATIONS
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
45′
40′
35′
118°30′
25′
34°
55′
50′
60
300
600
10
20
30
40
50

Figure 60. Depth to 60°F isotherm, August 18, 1955

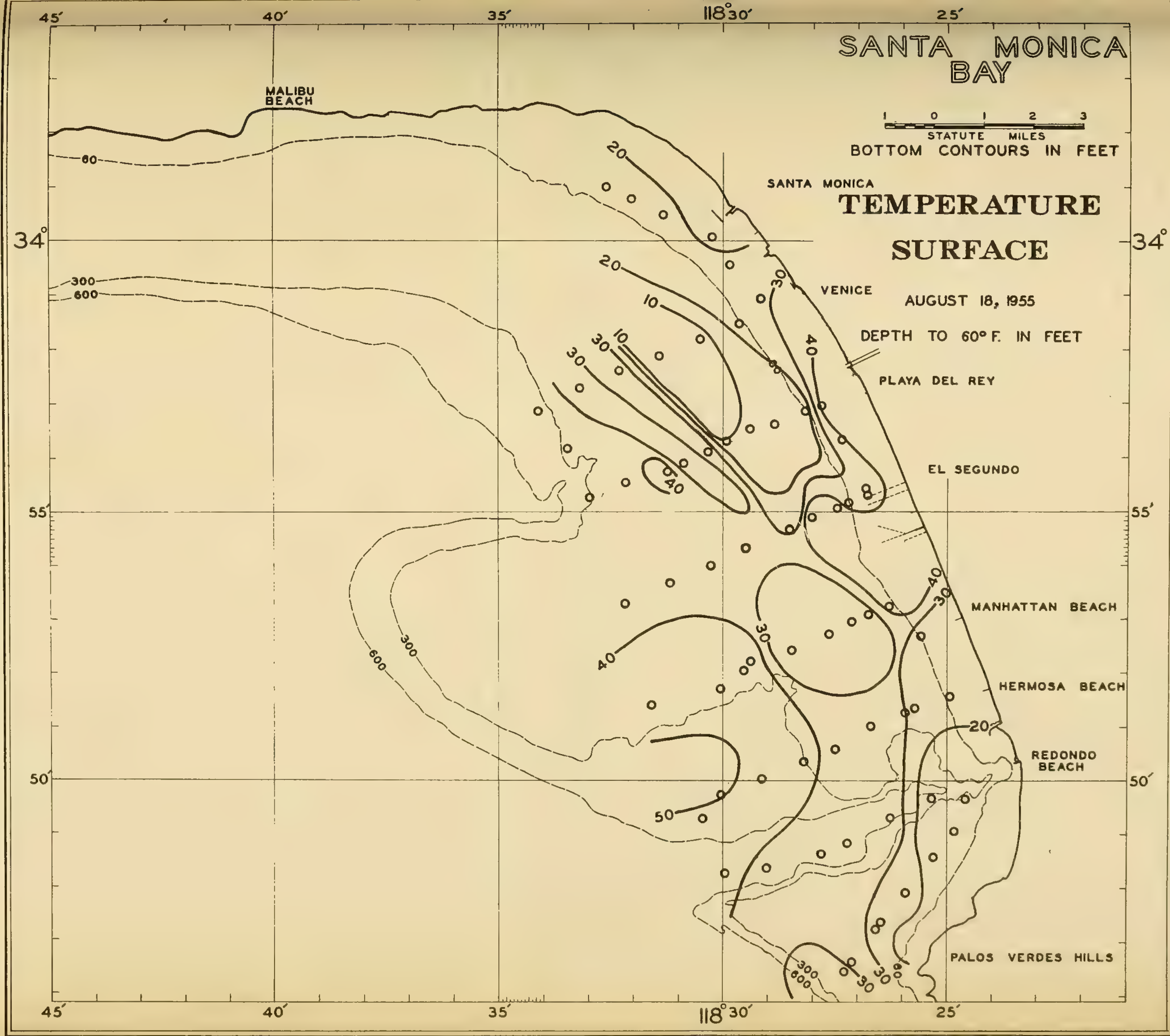

SANTA MONICA BAY
STATUTE MILES
BOTTOM CONTOURS IN FEET
TEMPERATURE
SURFACE
AUGUST 18, 1955
DEPTH TO 60° F. IN FEET
MALIBU BEACH
SANTA MONICA
VENICE
PLAYA DEL REY
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
34°
55′
50′
45′
40′
35′
118°30′
25′

Figure 61. Depth to $54^{\circ}F$ isotherm, August 18, 1955

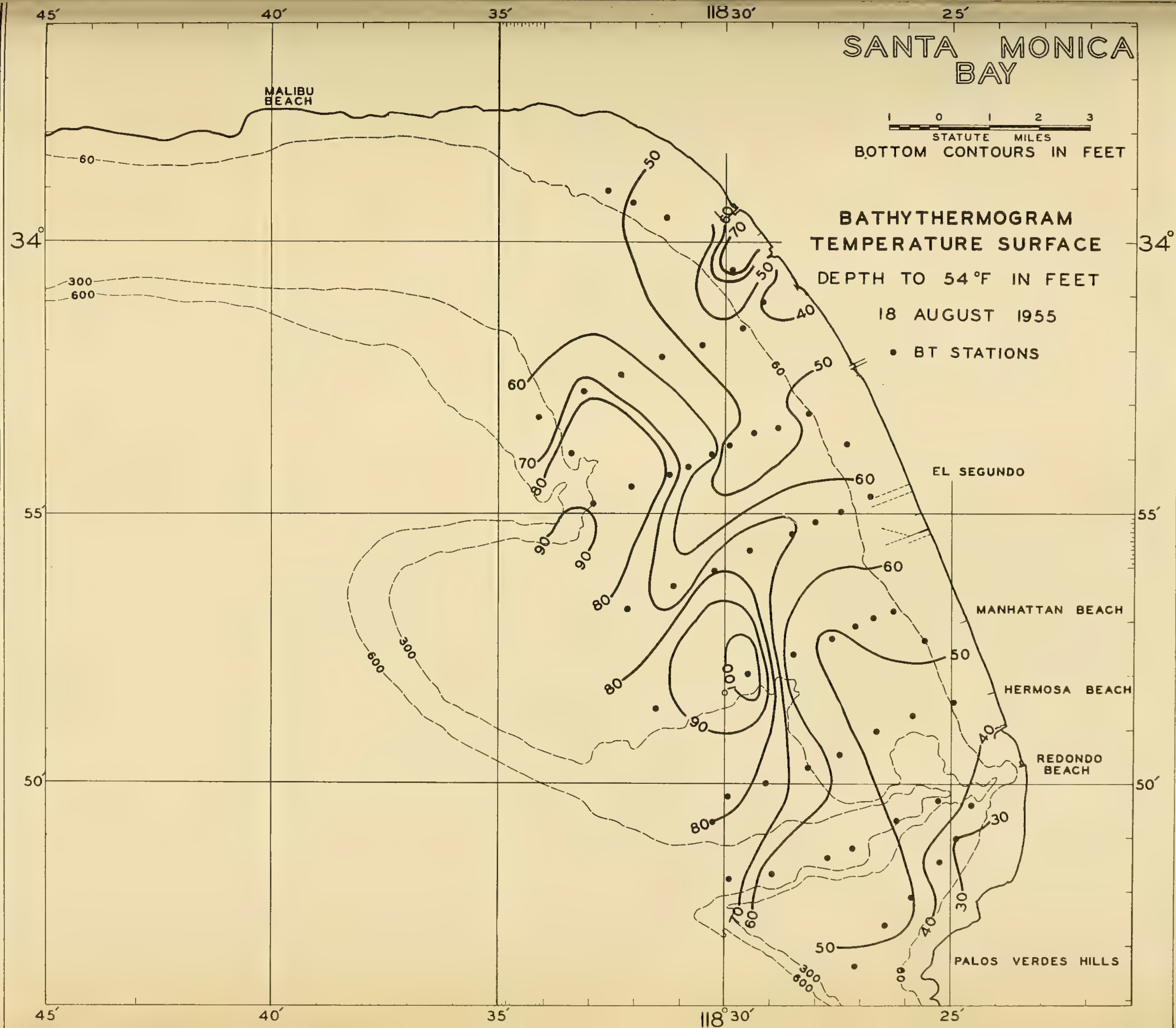

SANTA MONICA BAY
STATUTE MILES
BOTTOM CONTOURS IN FEET
BATHYTHERMOGRAM TEMPERATURE SURFACE
DEPTH TO 54°F IN FEET
18 AUGUST 1955
• BT STATIONS
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
45′
40′
35′
118°30′
25′
34°
55′
50′

Figure 62. Depth to 60°F isotherm, August 24, 1955

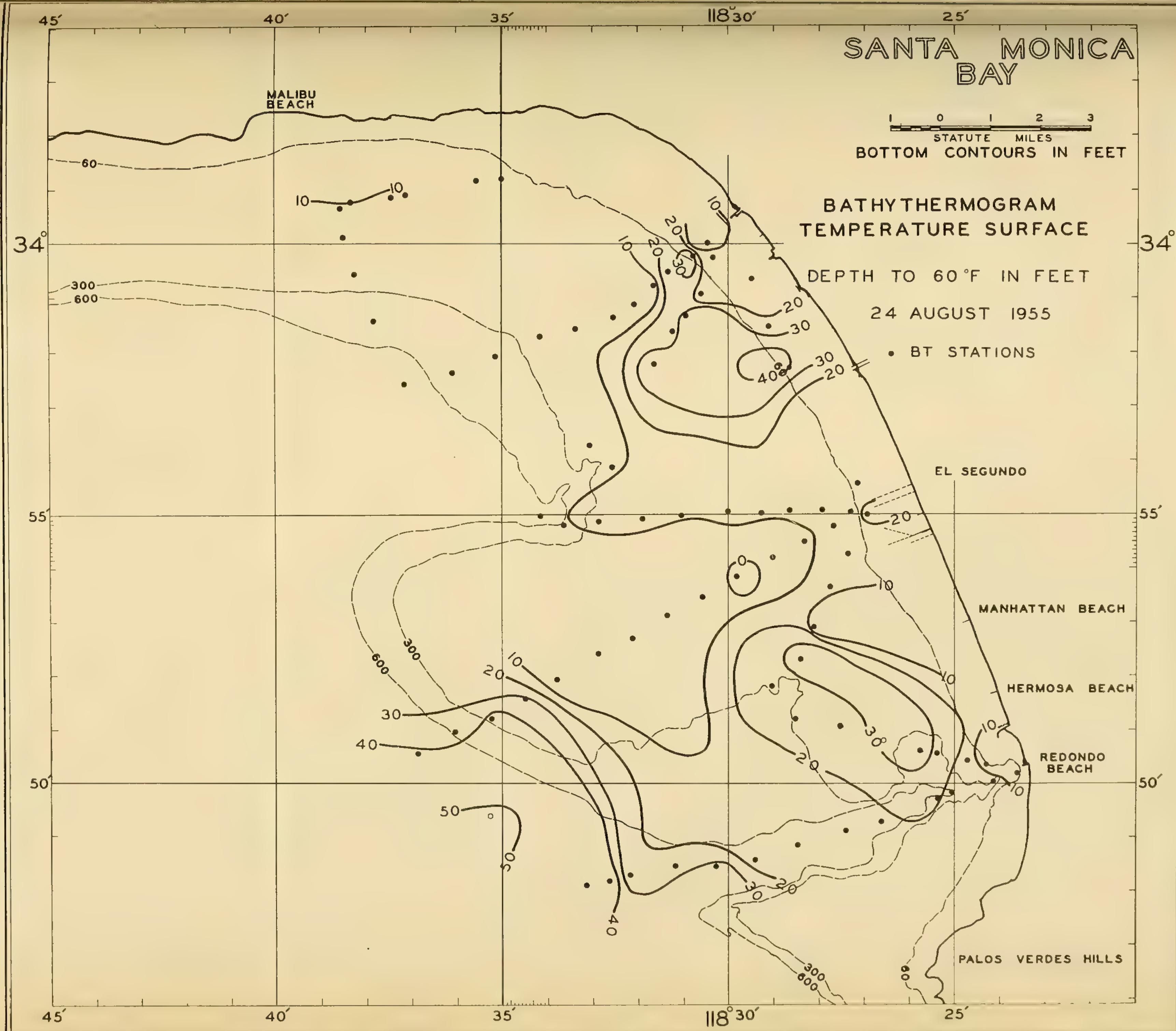
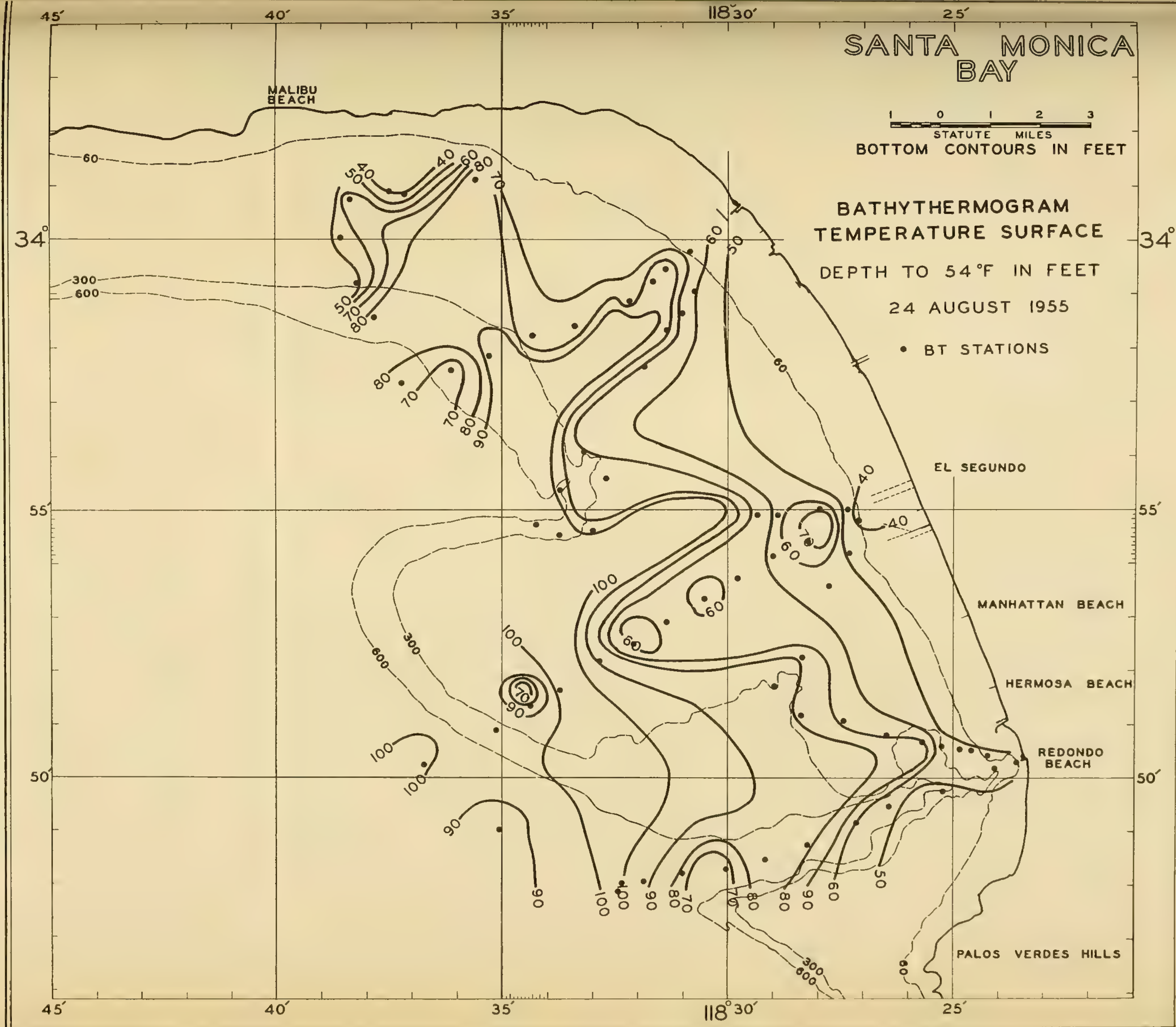

SANTA MONICA BAY
STATUTE MILES
BOTTOM CONTOURS IN FEET
BATHYTHERMOGRAM TEMPERATURE SURFACE
DEPTH TO 60°F IN FEET
24 AUGUST 1955
• BT STATIONS
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
118°30′
34°
55′
50′
45′
40′
35′
25′

Figure 63. Depth to 54°F isotherm, August 24, 1955


SANTA MONICA BAY
STATUTE MILES
BOTTOM CONTOURS IN FEET
BATHYTHERMOGRAM TEMPERATURE SURFACE
DEPTH TO 54°F IN FEET
24 AUGUST 1955
• BT STATIONS
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
118°30′
34°
55′
50′
45′
40′
35′
25′

A rather exceptional pattern occurred on the 10th of August; a pattern which was never repeated during the remainder of the survey. A large flat-surfaced gyral of warm water extended over the northern shelf with rather steep thermal slopes along the east and southern borders. A similar flat gyral, but of cold water extended over the southern shelf. Water motion generated by this pattern would be out the center of the bay directly opposite Hyperion. Wind drift would, of course, be dominant over most of the bay and with a strong west wind, the flow in the central portion would likely be negligible.

The upper temperature topography on August 24 had no thermal slopes of any magnitude. Nevertheless, upwelling is still present in the north and isolated but definitive warm areas occurred in the nearshore zone. In contrast, the subsurface topography was more complex and showed a definite trend of water motion to the south. There was a pattern directly seaward from Hyperion similar to that noted on August 18. In this pattern, however, the thermal slopes were more pronounced, although not as continuous; and in the absence of movement by the wind, it is more likely that a seaward flow existed.

The Surface Water Unit topography was similar on September 8 and 16, 1955, in that any water motion that did occur from temperature slopes was from the southwest into the Bay (Figs. 64 and 65). The thermal slope in the offshore area on the 8th was more pronounced than on the 16th, so it is presumed that wind drift was less a factor of importance on the earlier date.

Figure 64. Depth to $60^{\circ}F$ isotherm, September 8, 1955


SANTA MONICA BAY
1 0 1 2 3
STATUTE MILES
BOTTOM CONTOURS IN FEET
BATHYTHERMOGRAM TEMPERATURE SURACE
DEPTH TO 60 °F IN FEET
8 SEPTEMBER 1955
• BT STATIONS
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
118°30′
34°
55′
50′
45′
40′
35′
25′

Figure 65. Depth to 64°F isotherm, September 16, 1955


SANTA MONICA BAY
1 0 1 2 3
STATUTE MILES
BOTTOM CONTOURS IN FEET
BATHYTHERMOGRAM TEMPERATURE SURFACE
DEPTH TO 64 °F IN FEET
16 SEPTEMBER 1955
• BT STATIONS
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
34°
55′
50′
45′
40′
35′
118°30′
25′
60
300
600
10
20
30
40

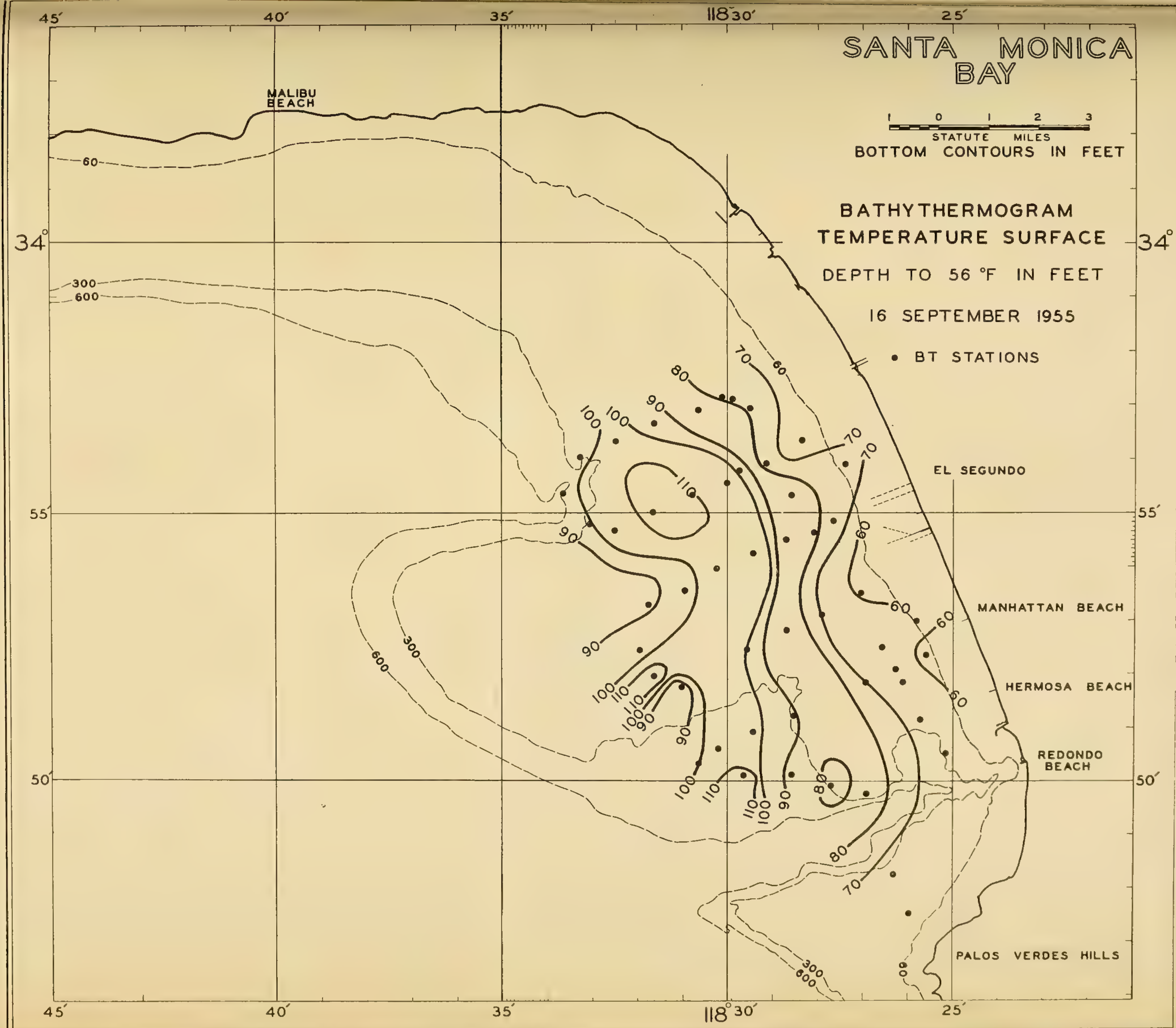
The subsurface distribution on these two days was similar over the outer shelf where again a flow to the northeast was indicated (Figs. 66 and 67). However, over the rest of the bay the two patterns were different; there being an irregular gradient on the 8th and a fairly smooth slope developing a southerly flow on the 16th. Similar conditions occurred on September 29, 1955 (Figs. 68 and 69).

The most complex pattern of temperature distribution gained from the data obtained during this survey is shown in Figures 70 and 71 of the surface and subsurface topographies on October 13, 1955. Even though it is conceivable and probable that temperature structures such as these exist, and perhaps more frequently than is supposed, it is believed that there were two outside contributing factors. First, the traverse lines and the bathythermograph stations were closer together than on any other survey. Minor variations in temperature, which normally would have gone unrecorded, were therefore observed, particularly in the nearshore area. Secondly, this cruise was a joint effort by the University of Southern California and the Bureau of Sanitation. Both bathythermographs were carefully checked and all temperatures reduced to the constant error between the surface temperature from bucket samples and that from the bathythermograph. Nevertheless, there is the distinct possibility that depth errors that are inherent to these instruments were enough different in the two bathythermographs to result in an unnatural depiction of the temperature topographies.

Figure 66. Depth to $55^{\circ}F$ isotherm, September 8, 1955


SANTA MONICA BAY
STATUTE MILES
BOTTOM CONTOURS IN FEET
BATHYTHERMOGRAM TEMPERATURE SURFACE
DEPTH TO 55 °F IN FEET
8 SEPTEMBER 1955
• BT STATIONS
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
34°
55'
50'
45'
40'
35'
118°30'
25'

Figure 67. Depth to 56^{o}F isotherm, September 16, 1955



SANTA MONICA BAY
STATUTE MILES
BOTTOM CONTOURS IN FEET
BATHYTHERMOGRAM TEMPERATURE SURFACE
DEPTH TO 56 °F IN FEET
16 SEPTEMBER 1955
• BT STATIONS
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
34°
55′
50′
45′
40′
35′
118°30′
25′

Figure 68. Depth to 61°F isotherm, September 29, 1955

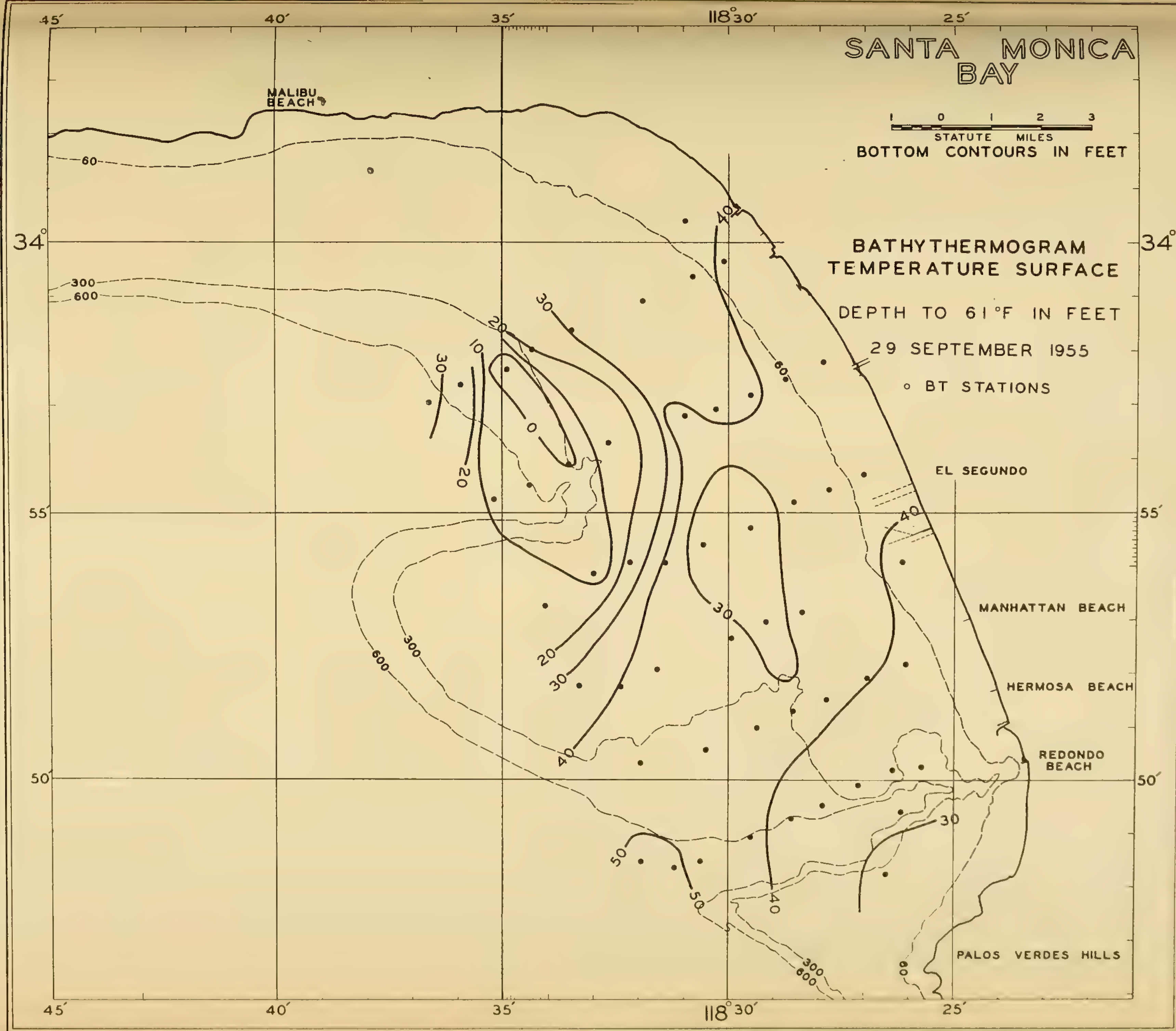

SANTA MONICA BAY
STATUTE MILES
BOTTOM CONTOURS IN FEET
BATHYTHERMOGRAM TEMPERATURE SURFACE
DEPTH TO 61°F IN FEET
29 SEPTEMBER 1955
∘ BT STATIONS
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
118°30′
34°
55′
50′
45′
40′
35′
25′

Figure 69. Depth to 55°F isotherm, September 29, 1955

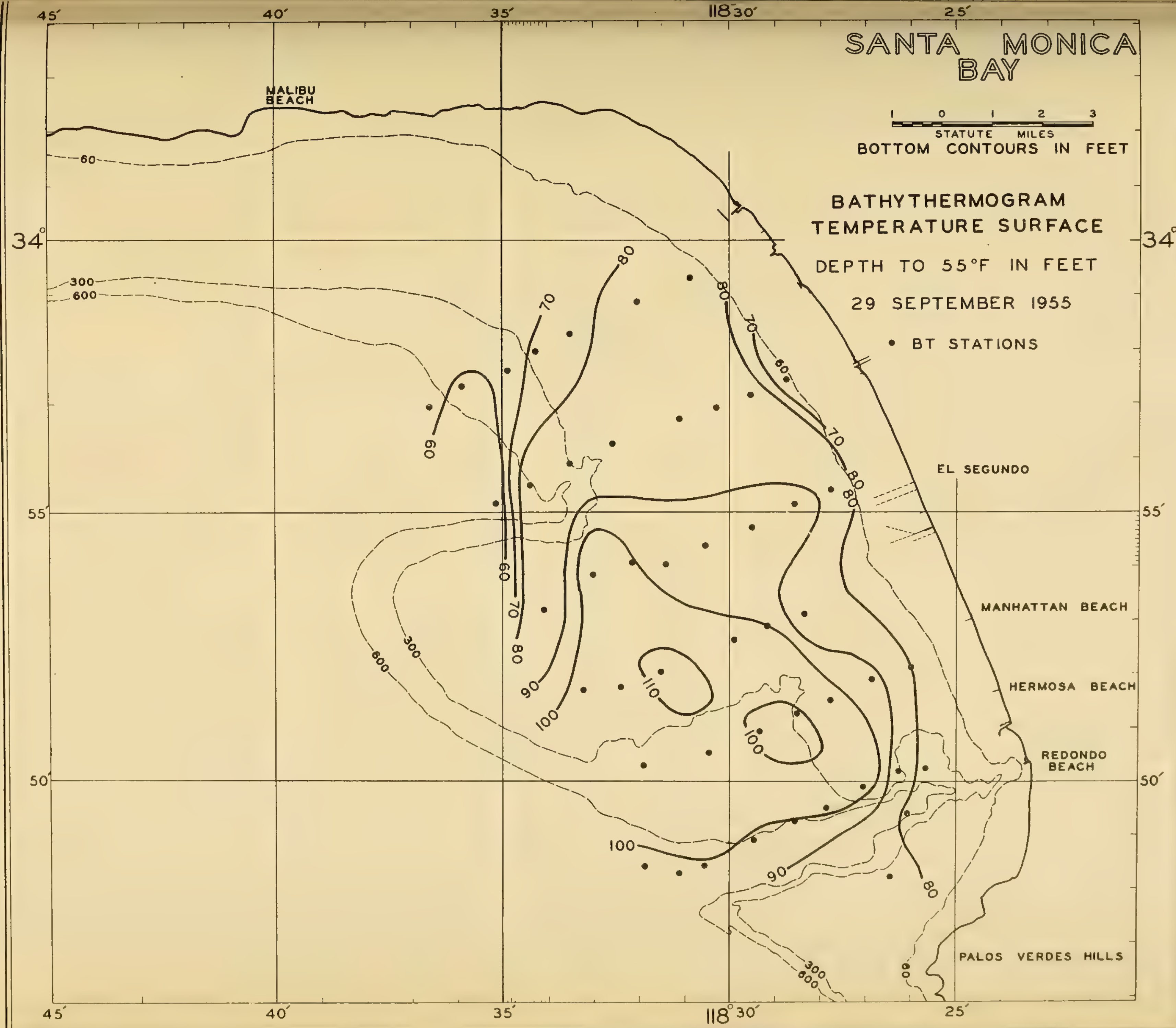

SANTA MONICA BAY
STATUTE MILES
BOTTOM CONTOURS IN FEET
BATHYTHERMOGRAM TEMPERATURE SURFACE
DEPTH TO 55°F IN FEET
29 SEPTEMBER 1955
• BT STATIONS
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS

Figure 70. Depth to $60^{o}F$ isotherm, October 13, 1955

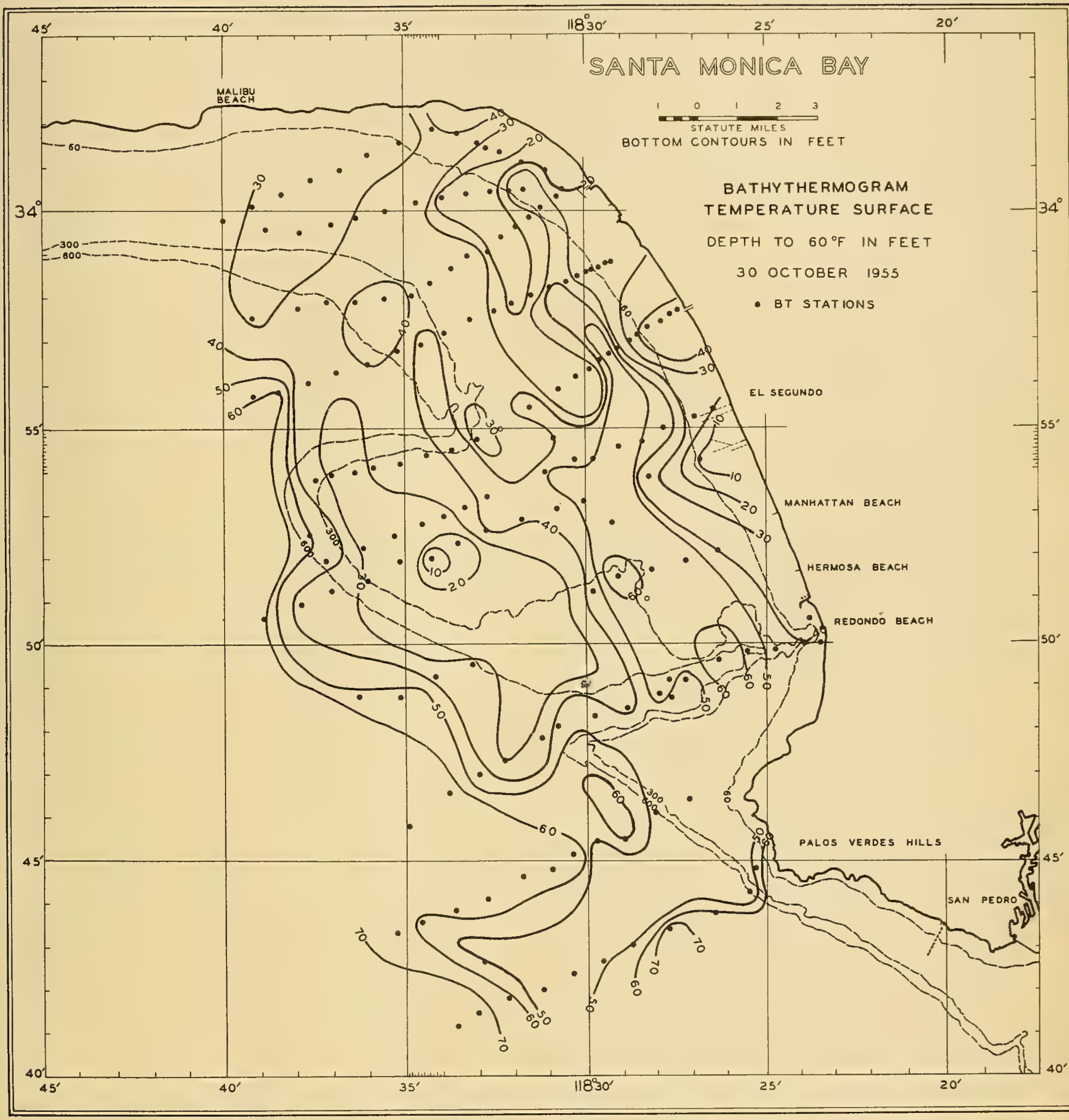
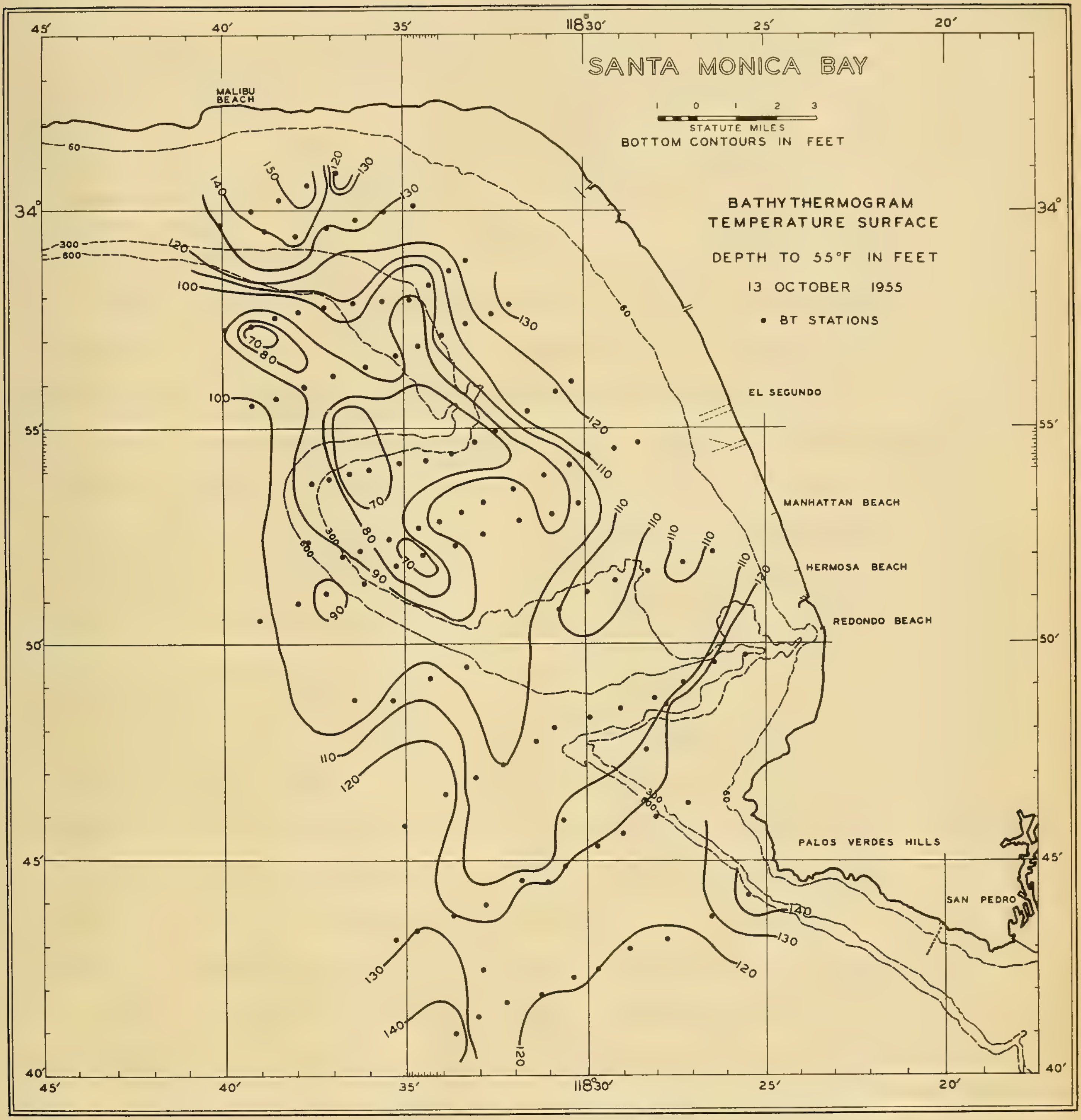

SANTA MONICA BAY
STATUTE MILES
BOTTOM CONTOURS IN FEET
BATHYTHERMOGRAM
TEMPERATURE SURFACE
DEPTH TO 60°F IN FEET
30 OCTOBER 1955
• BT STATIONS
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
SAN PEDRO
45′
40′
35′
118°30′
25′
20′
34°
55′
50′
45′
40′

Figure 71. Depth to $55^{\circ}F$ isotherm, October 13, 1955


SANTA MONICA BAY
STATUTE MILES
BOTTOM CONTOURS IN FEET
BATHYTHERMOGRAM
TEMPERATURE SURFACE
DEPTH TO 55°F IN FEET
13 OCTOBER 1955
• BT STATIONS
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
SAN PEDRO
45′
40′
35′
118°30′
25′
20′
34°
55′
50′
45′
40′

However, since the northern part of the bay from the Hyperion plant was covered by the Bureau of Sanitation, and the southern part by the University, and since the patterns resulting from the data in each section are continuous from one area to the other, it appears definitely reasonable to assume that the data as recorded are compatible and the patterns as shown are real. Furthermore, it is believed that had there been more opportunities when the two organizations could have conducted other joint surveys of this nature, that patterns of equivalent complexity would have been noted.

It is immediately apparent that the surface and subsurface topographies were almost identical on the 13th, with the normal departures expectable from the submarine topography and the variations in the external forces acting on the flow of ocean water. The center of the cold dome of water is displaced to the north in the subsurface water, for example, and the thermal slope along its eastern boundary is more continuous and pronounced. The temperature slope indicating a southerly flow nearshore in the surface layers is absent in the subsurface layer chosen because the 55 F isotherm intersected the sea floor seaward of the zone. Any flow established by thermal slopes was, of course, south and out of the bay in the offshore and southern areas. The indication of a northerly flow in the lower layers in the central part of the bay is not as well defined in the surface water, but the tendency is still present. That such patterns and consequent current action can and do exist is confirmed by data from the log of the VELERO IV on this and other days. Course corrections